THE EFFECT OF MONOLINGUALISM, BILINGUALISM AND TRILINGUALISM ON EXECUTIVE FUNCTIONING IN YOUNG AND OLDER ADULTS

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Abstract

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Key words: monolingualism, bilingualism, trilingualism, bilingual advantage, executive function, ageing, L2 acquisition, language use, hidden factors

Bilinguals have been posited to have, compared to monolinguals, enhanced cognitive control, consequently exhibiting greater cognitive reserve, which is thought to subsequently delay the onset of clinical expression of dementia. Based on recent evidence suggesting that the more languages one manages the greater cognitive reserve, and that trilinguals undergo greater exercise in language control than bilinguals, this thesis investigated the effects of trilingualism and ageing on cognitive control, in young adults to older adults. As the thesis investigated the novel field of trilingualism and cognitive control, task complexity, the age of second and third language acquisition, language use, and physical and cognitive activity were also, importantly, assessed, as these are possible influencing factors in test performance. The participants completed several cognitive tasks; namely the Simon task, the Inhibition of return task, the Stroop task (inhibition) and the N-back task (working memory). The novel discovery of a trilingual (and bilingual) disadvantage was observed, which could explain some previous inconsistent findings in the bilingualism literature, where trilingualism may influence bilinguals' test performance, as trilinguals and multilinguals are often mixed in with the bilingual group. Furthermore, the results suggest that second language acquisition and language use does not consistently predict performance in trilinguals (and bilinguals), nor does cognitive activity, although physical activity may modulate language group differences. Importantly, the results from this novel investigation of the effects of trilingualism and ageing on cognitive control suggest that trilingualism (and bilingualism) can, in some cases, be detrimental to cognitive control.

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List of abbreviations

ACC	Accuracy
AD	Alzheimer’s disease
ADHD	Attention deficit hyperactivity disorder
aMCI	Amnestic mild cognitive impairment
ANCOVA	Univariate Analysis of Covariance
AoA	Age of acquisition
APOE	Apolipoprotein E
BR	Brain reserve
CIND	Cognitive impairment no dementia
CogA	Cognitive activity
CR	Cognitive reserve
CS	Compensatory scaffolding
CT	Computerised tomography
FTLD	Frontotemporal lobar degeneration
EEG	Electroencephalographic
EF	Executive function/functioning
GLM	General linear model
IOR	Inhibition of return
L1	First language
L2	Second language
L3	Third language

MANCOVA	Multivariate Analysis of Covariance
MCI	Mild cognitive impairment
MMSE	Mini Mental State Examination
naMCI	Non-amnestic mild cognitive impairment
OMCT	Orientation Memory Concentration Test
PFC	Prefrontal cortex
PhysA	Physical activity
PNT	Picture naming test
RCT	Randomized controlled trial
RT	Reaction time
SAS	Supervisory Attentional System
SD	Standard deviation
SE	Standard error
SES	Socioeconomic status
SOA	Stimulus onset asynchrony
SRC	Stimulus-response compatibility
STAC	The Scaffolding Theory of Aging and Cognition
WCST	Wisconsin Card Sorting Test
WM	Working memory

Chapter 1: Thesis overview

1.1 Introduction and aims

Speaking more than one language is common among millions of people all over the world (Lewis, 2009). A survey carried out by the European Commission (2012) observed that 54% of the respondents across all European Union countries claimed they were functionally fluent in at least two languages, and 25% in at least three languages. According to the Office for National Statistics (ONS, 2013) 7.7% of the population of England (aged three and over) had another language than English as their main language.

Growing evidence indicates that, within this population, cognitive advantages such as enhanced cognitive control (executive functioning - EF), are associated with bilingualism, and that the responsible underlying mechanism for this enhanced cognitive control appears to be the bilinguals' cognitively demanding experience of managing two language systems (bilingual language control). There is also evidence that lifelong bilingualism delays the onset of clinical expression of dementia, and that this is potentially due to bilinguals' enhanced cognitive control; hence cognitive reserve. Based on this knowledge, and the importance of delaying the clinical expression of dementia for as long as possible, it needs to be determined whether this proposed cognitive reserve of bilingualism can be extended to trilingualism, in order to even further delay the debilitating effects of dementia.

To shed light on this question, the main aim of this thesis was to extend the investigation of bilingualism and cognitive control to trilingualism – to examine whether the proposed cognitive control advantage is stronger in trilinguals than in bilinguals, and can, therefore, offer more cognitive reserve. This is based on the premise that managing three languages, compared to two, provides greater exercise in language control, which, in turn, results in stronger cognitive control. This will be investigated in young and older monolingual, bilingual and trilingual adults as increased neuroplasticity has been reported in bilinguals (compared to monolinguals) of both age groups. Various EF tasks will be utilised, focusing on inhibitory control, monitoring and WM, as evidence suggests that these three processes are enhanced in bilinguals, although limited research has been conducted on WM using complex WM tasks. There is evidence, however, that inhibition and WM may share an underlying mechanism; thus, studying WM is important in this context. This thesis also explores task complexity as it has been argued that the effects of the bilingual advantage are most likely to be seen in young adults, under more complex conditions. Furthermore, the role of age of acquisition (AoA) of a second language (L2) and third language (L3), and absolute language use will be investigated, as well as possible confounding factors known to attenuate age-related cognitive decline and contribute to cognitive reserve, namely physical and cognitive activity. This thesis also speculates as to whether previous research in the literature may be confounded by the presence of trilinguals in "bilingual" cohorts (see discussion throughout thesis). Before providing an overview of the thesis, the concepts bilingualism and trilingualism will be introduced.

1.2 Defining bilingualism and trilingualism

It is difficult to define bilingualism as what it entails is dynamic in nature. For instance, bilinguals have diverse language backgrounds, due to various reasons leading to their bilingualism (Grosjean, 2010). The present thesis takes a similar view as Grosjean (2010) on the definition of bilingualism. He argues that the definition of bilingualism should not be reduced to early acquisition and native fluency of both languages, as this does not describe the majority of bilinguals. Grosjean (2010) further states that it is language use, in particular, which should be focused on, whereby an individual can be classified as bilingual if she or he uses two or more languages on a regular basis. This view acknowledges that an individual who did not acquire both languages in early childhood, does not speak both languages in the home, does not live in a two-language community, was not schooled in both of her or his languages, has an accent in one of her or his languages, can still be classified as a bilingual (Grosjean, 2010). There is, however, one complication with regard to Grosjean's (2010) definition of a "bilingual", which is also an issue in the neurolinguistic literature (see Higby et al., 2013). Grosjean (2010) classifies individuals who speak two or more languages, such as trilinguals, as "bilinguals" too. This is also an apparent issue in the bilingualism and cognition literature. The literature review journey revealed several papers, where it is stated that participants who speak more than two languages have been classified as bilinguals. For the purpose of this thesis individuals are considered bilinguals if they acquired their second language from birth and onwards, and participants are considered trilinguals if they acquired their second and third languages from birth onwards. The effects of L2 (and L3 for trilinguals) will be looked at in a later chapter, and having this wide range of AoA is important as the effects of AoA will be examined on a continuum. See Table 1 for key definitions used in this thesis.

Table 1. Key to monolingualism, bilingualism and trilingualism definitions for the purpose of this thesis

Monolingual	Only functionally fluent in one language, and only uses one language on a daily basis.
Bilingual	Functionally fluent in two languages, and uses both on a daily basis.
Trilingual	Functionally fluent in three languages, and uses all on a daily basis.
Multilingual	For the purpose of this thesis, a multilingual is an individual who speaks three or more languages. Thus, a trilingual can be referred to as a trilingual (only speaks three languages), or as a multilingual if being referred to as a part of a language group that speaks three or more languages.
L1	The first language an individual is exposed to/acquires. If the bilingual or trilingual is simultaneous (see below) the more/most dominant language is referred to as L1 in this thesis.
L2	The second language an individual is exposed to/acquires.
L3	The third language an individual is exposed to/acquires.
Simultaneous bilinguals	Bilinguals who start acquiring both languages from birth, or in the first two to three years of life (Costa and Seastián-Galles, 2014).
Successive bilinguals	Bilinguals who start acquiring their second language (L2) once their first language (L1) has been established (although as of yet there is not a general consensus in the literature as to how well L1 needs to be established before referring to an individual as successive), and can this be in early childhood (early successive) or later in life (late successive) (Costa and Seastián-Galles, 2014).
AoA	Age of acquisition

1.3 Overview of thesis structure

The thesis consists of eleven chapters. The following section presents a brief overview of each chapter:

Chapter 2 provides a general introduction to cognitive ageing, cognitive reserve and dementia, suggesting how bilingualism and multilingualism may contribute to cognitive reserve, and ultimately delay the onset of dementia diagnosis.

Chapter 3 gives a general introduction to EF (cognitive control), which have been implicated in the bilingual advantage, and a more in depth overview of inhibition, monitoring, and WM as these three mechanisms were investigated in this thesis.

Chapter 4 provides an overview of the bilingualism and cognition literature, focusing on bilinguals' effect on cognitive control, the underlying mechanisms of bilinguals' proposed enhanced cognitive control, the possible confounding effect of classifying trilinguals/multilinguals as bilinguals, and, lastly, speculates whether more languages equals stronger language control, and thus stronger cognitive control.

The experiment of **Chapter 5**, investigates the proposed bilingual advantage in inhibitory control and monitoring in trilinguals, as well as age-related effects, examined on a continuum. The data from the Simon task showed a trilingual disadvantage (compared to monolinguals and bilinguals) in inhibitory control, but only after around 29 years of age.

The experiment of **Chapter 6** examines WM performance and possible age-related effects on a continuum. All participants completed a complex, numerical version of the n-back task (1-back and 2-back). This version of the task had not been previously employed in trilinguals, or bilinguals in the literature. A trilingual disadvantage was observed in both 1-back and 2-back (both match and non-match trials), as well as in the n-back effect (match). A bilingual disadvantage was also seen in 1-back and 2-back (non-match). No clear differences were found between bilinguals and trilinguals. Age-related decline was observed in terms of response time, but not accuracy of response, and this was not modulated by language group.

The experiment of **Chapter 7** investigates the bilingual advantage in trilinguals in another type of inhibitory control (the inhibition of return (IOR) effect – a bias against returning attention to previously attended locations) – and age-related effects (on a continuum). All participants completed an IOR task, which had not been previously employed in trilinguals or older bilinguals. A trilingual disadvantage was shown in global RT (monitoring), but no statistical differences in terms of the cueing effects (IOR or facilitation). An age-related decline was observed, both in terms of accuracy of response, global RT, and for the IOR effect. However, this was not modulated by language group.

The experiment of **Chapter 8** investigates the proposed bilingual advantage in trilinguals on another type of inhibitory control, measured by the Stroop colour-word task. Performance on this task had not been investigated prior to the start of this project, comparing young to older monolinguals, bilinguals and trilinguals. A trilingual disadvantage was seen in inhibitory control, consistent with results from the Simon task, but not the IOR task. An age-related decline was observed on both congruent and incongruent conditions of the task, although, again, this was not modulated by language group.

The experiment of **Chapter 9** investigates the bilingual advantage in trilinguals and task complexity, using the Simon (two levels of complexity) task and N-back task (four levels of complexity). This is important to study in young trilinguals, as prior research indicates that in young adults – the age group the bilingual advantage is least likely to be seen – the advantage may only become apparent on more complex conditions of cognitive tasks (Bialystok et al., 2014; Morales et al., 2013; Bialystok, 2006). Also, this was particularly important to assess given the bilingual and trilingual disadvantage results in previous chapters of this thesis. In the Simon task, a trilingual disadvantage was observed, in the complex condition, but only in terms of accuracy of response. Although several trends were observed, no other language group statistical differences were seen. In the N-back task, no language group differences were seen; that is, the groups did not differ under any level of complexity, or increasing WM load between 0-back and the more complex conditions (1-back, 2-back and 3-back).

Chapter 10 investigates whether language acquisition and language use predicted bilinguals and trilinguals' test scores, from three data sets of the thesis (from Chapters 5, 6, 7 and 8). This is important to investigate because the literature on both factors is inconsistent, and particularly significant in trilinguals, as this thesis is a new area of research. The data suggest that the age of language acquisition did not predict any of the bilinguals or trilinguals' test scores, providing new evidence that for trilinguals, L2 and L3 AoA does not modulate cognitive control. Language use did not predict any of the test scores among trilinguals, again, providing new evidence that for trilinguals, language use does not modulate cognitive control. Language use did not consistently predict test scores for bilinguals, although some of its effects were seen on the N-back WM task, indicating worse performance for more dominant bilinguals.

Chapter 11 investigates whether physical activity and cognitive activity of the participants could explain the findings from the same three data sets as were used in Chapter 10. Cognitive activity did not predict any of the test scores, but the data suggest that physical activity may have some modulation effect, although this was not consistent.

Chapter 12, the general discussion chapter, summarises the main findings of the thesis and discusses the implications of these findings for the bilingualism/trilingualism and cognition literature, as well as the neuropsychology literature, and possible future work and improvements identified.

Chapter 2: Cognitive ageing, dementia and cognitive reserve

2.1 Introduction

Due to extended life expectancy, the aged population is on the increase. This pattern is predicted to continue, and it is currently estimated that in 2035, individuals aged 65 and over will account for 23%, and individuals aged 85 and over account for 5%, of the total UK population (ONS, 2012). In fact, those aged 85 and over are currently the fastest growing population, and have doubled between 1985 and 2010, from nearly 0.7 million to over 1.4 million individuals, and it is estimated this number will have increased to 3.5 million by 2035 (ONS, 2012). Consequently, due to economic reasons, people are expected to work longer, and the UK government is planning to gradually increase the state pension age to 67 years between 2026 and 2028 (Department for Work and Pensions, 2013).

Logically, this means that older adults need to stay both physically and cognitively fit for longer. However, older adults tend to exhibit biological, physiological, and behavioural decline in function, which in turn extends to cognitive functioning, some aspects of which have been found to significantly decline between early adulthood (20s) and the 80s (Park and Reuter-Lorenz, 2009; Salthouse, 2009a). Also, the incidence of dementia is on the increase. In the UK, 850,000 individuals are expected to be living with dementia in 2015, and one in every 14 of the UK population aged 65 years and over has dementia. This is currently costing the UK 26 billion per year (Alzheimer's Society, 2014). Thus, it is imperative to further the understanding of how to attenuate, or prevent the age-related cognitive decline, both for healthy ageing, and for understanding neurodegenerative diseases, such as Alzheimer's disease (AD).

As this chapter will show, the investigation into how to maintain cognitive health has been one of the main aims of the recent neurocognitive ageing literature. Various indicators – such as education, physical and cognitive activeness, bilingualism and multilingualism – have been proposed to prolong healthy cognitive ageing, and to delay the onset of clinical expression of dementia. Concepts such as brain reserve (BR) (Satz, 1993), cognitive reserve (CR) (Stern, 2002) and compensatory scaffolding (Reuter-Lorenz and Park, 2014; Park and Reuter-Lorenz, 2009) have been hypothesised as possible mechanisms capable of assisting in this context. Nevertheless, these indicators and compensation mechanisms are still not fully understood. For instance, the underlying source of why bilingualism and multilingualism are thought to delay the onset of clinical expression of dementia, is still not fully understood.

2.2 Healthy cognitive ageing

Both structural and functional neural changes are associated with healthy ageing. Grey matter volume is reduced as we age, most profoundly in regions including the frontal and parietal cortices, and the hippocampus (Crivello et al., 2014; Thambisetty et al., 2010; Driscoll et al., 2009; Fjell et al., 2009; Resnick et al., 2003). Furthermore, white matter volume has been found to become less dense and lose integrity (Bennet and Madden, 2014; Fjell et al., 2013; Madden et al., 2012; Salat et al., 2011; Barrick et al., 2010; Gunning-Dixon et al., 2009).

These age-related neural changes lead to a decline in various cognitive domains, including episodic memory, processing speed, and EFs, such as WM and inhibitory control (Grady, 2012; Reuter-Lorenz and Park, 2010; Takio et al., 2009; Kray et al., 2004; Zelazo et al., 2004). EFs, which will be introduced in Chapter 3, have been described as an umbrella term, consisting of several distinct, but related processes; inhibition, updating WM and task-switching (Miyake and Friedman, 2012; Friedman et al., 2008; Miyake et al., 2000).

The trajectory of the ageing process on cognitive function is, however, heterogeneous and complex. For instance, there is also evidence to suggest that other functions are maintained with age. These include vocabulary (Singh-Manoux et al., 2011; Laver, 2009; Park and Reuter, 2009; Salthouse, 2009b; Park et al., 2002) and emotional regulation (Carstensen et al., 2011, 2003). Furthermore, the rate at which individuals experience the age-related cognitive decline varies, whereby some individuals maintain cognitive function longer than others (Brayne, 2007). Also, the age at which cognitive processes peak and start to decline differs (Hartshorne and Germine, 2015; Salthouse, 2009a), and although some evidence suggest that age-related cognitive decline does not become apparent until after approximately 60 years of age (Rönnlund et al., 2005; Hedden and Gabrieli, 2004; Aartsen et al., 2002), other evidence indicates that this begins earlier (Finch, 2009; Salthouse, 2009a). In fact, Salthouse (2009a) concluded that some aspects of cognitive functioning, such as memory, reasoning, spatial visualisation and processing speed, begin to decline in early adulthood (in the 20s and 30s). A recent longitudinal study by Singh-Manoux et al. (2011) further supports earlier cognitive decline. Seven thousand and four hundred and fifty four individuals, aged 33 to 55 years at baseline, were assessed three times over ten years. The cognitive functions under investigation were memory, reasoning, vocabulary and fluency. Singh-Manoux and colleagues (2011) reported cognitive decline over the ten year period for memory, reasoning and fluency, but not vocabulary.

Thus far, this literature review has shown that a complex variability in age-related cognitive performance exists. The tendency is for this variability to increase as we age, and in the context of neurodegenerative diseases, such as AD, and other forms of dementia (Tucker and Stern, 2011). Although healthy ageing studies should only include individuals in good health, early symptoms of dementia, such as mild cognitive impairment (MCI) related symptoms, can be missed and mistaken for normal age-related cognitive decline (Harada et al., 2013).

2.3 The bridge between healthy cognitive ageing and dementia; mild cognitive impairment (MCI)

In the past decade, much ageing research has focused on early diagnosis of dementia; to identify early signs and symptoms that predict whether individuals are at risk of developing AD. MCI is one of the concepts proposed to capture the grey area between healthy cognition and dementia (Petersen et al., 2014; Reitz and Mayeux, 2014). It is characterised by memory and cognitive complaints (Albert et al., 2011), and has been described as a useful label to identify those who are at risk of developing AD (Petersen et al., 2014; Reitz and Mayeux, 2014). MCI is classified as amnestic MCI (aMCI) if memory is primarily affected, and non-amnestic MCI (naMCI) if other cognitive domains other than memory are affected, such as language, or EFs. MCI can be further divided into single domain MCI, where only one cognitive domain is impaired, or multiple domain MCI (Petersen et al., 2014). Some evidence suggests that if individuals have multiple domain aMCI they are at higher risk of being diagnosed with dementia (Busse et al., 2006; Alexopoulos et al., 2006).

2.4 Dementia

Dementia, which comes in many forms, is cognitively characterised by memory loss and cognitive impairment in multiple domains. The general brain deterioration features of dementia are brain atrophy and larger lateral ventricles due to reduced brain mass (Frisoni et al., 2010). The exact cause of dementia and its interrelated brain deterioration is not fully clear (Frisoni et al., 2013). The most prevalent subtypes of dementia are AD, vascular dementia, dementia with Lewy bodies and frontotemporal lobar degeneration (FTLD) (Alzheimer’s Society, 2014; Rossor et al., 2010), although evidence suggests that mixed subtypes, such as AD (neurodegenerative) and vascular combined account for most cases of dementia (Viswanathan et al., 2009; Schneider et al., 2007; Neuropathology Group, 2001).

AD is characterised by two pathological factors; amyloid plaques and tau neurofibrillary tangles, and at present, an AD diagnosis is only a probable diagnosis, as a definite diagnosis can only be made at post mortem (Ballard et al., 2011). The pathological changes associated with these factors are thought to gradually progress for at a minimum of 20 to 30 years before the onset of clinical expression of symptoms (Braak et al., 2008). Apart from age, certain risk factors, both genetic, non-genetic, and environmental are associated with AD (for a review, see Reitz and Mayeux, 2014). These include the APOE-4 gene (Slooter et al., 1998), traumatic brain injury (Jellinger et al., 2001) and type 2 diabetes (Luchinger et al., 2001). The potential protective factors include diet and cognitive reserve (Reitz and Mayeux, 2014; Ballard et al., 2011). Cognitive reserve will be introduced in section 2.5.

This section has given a brief introduction to dementia and its most prevalent subtype, AD. As mentioned earlier, there is evidence to suggest that, as in the context of healthy cognitive ageing, certain factors can affect the trajectory of AD, which can be explained by compensation mechanisms, such as cognitive reserve.

2.5 Compensation mechanisms

A growing body of evidence suggests that a number of factors attenuate healthy age-related cognitive decline, and slow down the process of developing dementia. Although the underlying source of this association is not fully understood, it has been proposed that this can be explained by ‘reserve’. The notion of reserve stems from the observation that some individuals are better able to function than others, despite showing neuropathology (Stern, 2002). That is, for some individuals, there does not seem to be a direct relationship between the severity of brain damage and the clinical symptoms of that damage (Stern, 2002). In line with this, studies of ageing have reported that 25% to 67% of elderly individuals, who met full pathologic criteria for AD after death, did not show any signs of cognitive impairment prior to death (for a review, see Tucker and Stern, 2011).

As previously mentioned, several models of ‘reserve’ have been proposed to explain why some individuals seem to cope better with neuropathology. These include brain reserve (BR) (Satz, 1993) and cognitive reserve (CR) (Stern, 2002). Other models have been proposed to account for this, including brain maintenance (Nyberg et al., 2012) and The Scaffolding Theory of Aging and Cognition (STAC-r) (Reuter-Lorenz and Park, 2014; Park and Reuter-Lorenz, 2009). The BR, CR and STAC-r models will be introduced in the following sub-sections.

2.5.1 Brain Reserve (BR)

The BR hypothesis focuses on the structure of the brain. It proposes that individuals differ in terms of brain volume and other quantitative aspects of the brain (such as quantity of neurons and synapses available), and those with more brain reserve capacity (larger brains for instance) have more resilience against neurodegeneration (Satz, 1993). The greater the reserve, the more neuropathological damage is needed before cognitive impairments become apparent (Satz et al., 2011; Sachdev and Valenzuela, 2009; Satz, 1993).

Initially, it was posited that BR was a passive model of reserve, as it was not thought to take into account the individual variability in cognitive performance, which may in turn lead to different outcomes from pathology derived from dementia (Stern, 2009, 2002). However, this view was recently challenged by Satz et al. (2011), who maintain that BR is not as passive as previously thought, since evidence shows that the brain can actually be altered by experience, via neurogenesis for instance (Satz, et al., 2011). Evidence for this comes for example from studies looking at the structural effects of physical activity and exercise on the brain, which have found these to have enhancing effects on brain health (Erickson et al., 2013; Voss et al., 2013; Hillman et al., 2008). In terms of brain structure, aerobic exercise, for example, has been shown to increase structural plasticity (Voss et al., 2013; Colcombe et al., 2006). This was particularly prominent in prefrontal and temporal regions, which have often been shown to demonstrate considerable age-related deterioration (Ziegler et al. 2012). Physical activity has also been shown to maintain white matter health in older adults of low fitness (Burzynska et al., 2014) and in physically fit older adults with lifelong exercise experience (Tseng et al., 2013). Physical activity will be looked at in Chapter 11. This is important for EFs (see Chapter 3), which are associated with the frontal lobes, mostly in the prefrontal cortex, as well as in other regions (Jurado and Rosselli, 2007). White matter is responsible for the connectivity between brain regions, where stronger connectivity means faster information transfer, resulting in better executive performance (Filley, 2010).

2.5.2 CR

In contrast to BR, CR focuses on the function of the brain; that is, how the brain's resources (cognitive networks) are adaptably used to function in the presence of neuropathology (Stern, 2002). As mentioned earlier, it has been suggested that different life experiences contribute to cognitive reserve. These include higher level of education (Meng and D'Arcy, 2012; Wilson et al., 2009; White et al., 1994), occupation (Massimo et al., 2015; Woollett and Maguire, 2011; White et al., 1994), engaging in social activities (Amieva et al., 2010; Crowe et al., 2003; Scarmeas et al., 2001) and physical activities (Gow et al., 2012; Verghese et al., 2003; Fabrigoule et al., 1995). Furthermore, evidence suggests that engaging in cognitively stimulating activities, such as reading, writing, attending lectures, playing word games, doing crossword puzzles, and playing card games, both early and later in life, is associated with enhanced cognitive function and consequently attenuates age-related cognitive decline (Wilson et al., 2013; Reed et al., 2011; Lachman et al., 2010; Plassman et al., 2010; Stern, 2009; Sing-Manoux et al., 2003). This will be examined in Chapter 11.

It needs noting that it is very difficult to determine how exactly each of these factors impact cognitive performance, as they are likely to confound each other (Jones et al., 2011). For example, if education is taken as a measure of cognitive reserve (the more years of education the more reserve) it may predict cognitive performance in older adults because it contributes to cognitive reserve, or the cognitive performance could be confounded by age, as both education and cognitive performance may be predicted by age (Jones et al., 2011). Furthermore, there is also evidence that cognitive ability is hereditary, and thus, some of the variability in the observed age-related cognitive decline/changes can be accounted for by genetics. For instance, a twin study (McClearn et al., 1997) investigated general and specific cognitive abilities in 240 twin pairs, between the ages of 80 and 95 years, and estimated that 62% of general cognitive ability, 52% of memory, 62% of processing speed and 32% of spatial ability can be attributed to genetics. This does not, however, indicate that environmental influences are lacking. McClearn et al. (1997) also found that approximately 40% of the variance for general cognitive ability (and more for specific cognitive abilities) could be explained by environmental influences.

2.5.3 The Scaffolding Theory of Aging and Cognition (STAC)

The STAC is perhaps the most comprehensive and flexible compensation model proposed thus far (see Figure 1). It was put forward by Park and Reuter-Lorenz (2009), and then more recently, a revised model (STAC-r) was proposed by same authors (Reuter-Lorenz and Park, 2014), incorporating new evidence on the brain and ageing.

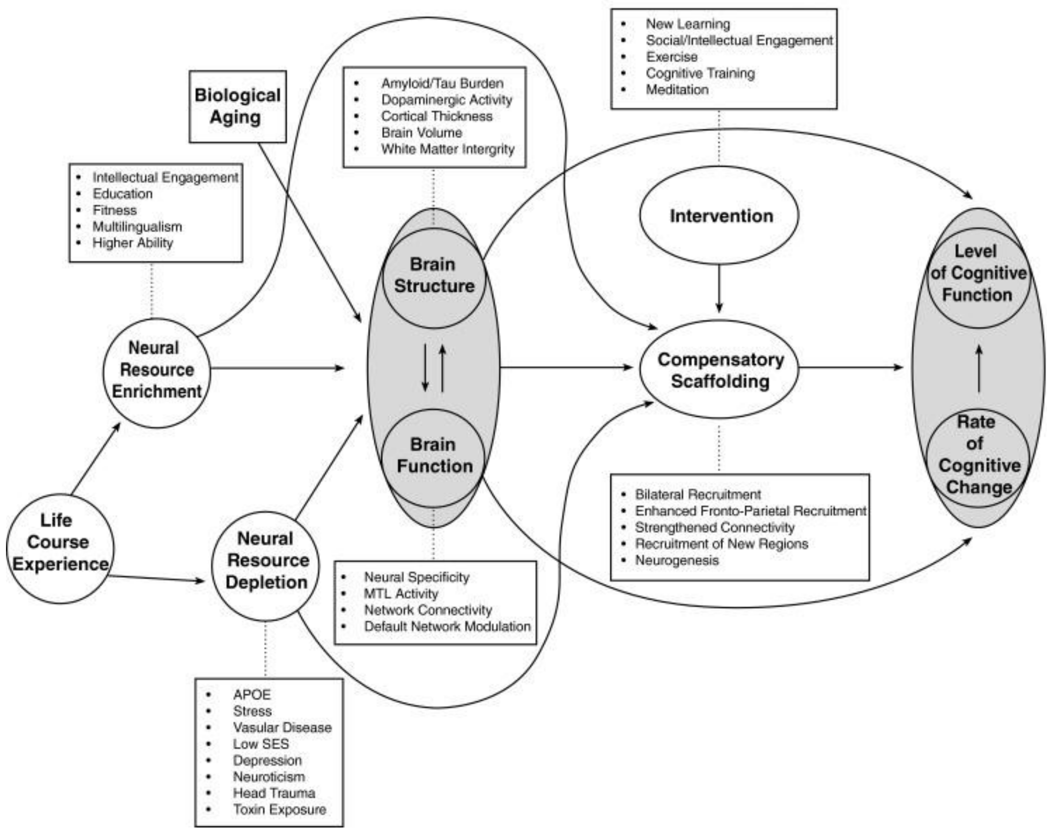

Figure 1 showing a revised (STAC-r) conceptual model of the scaffolding theory of ageing and cognition. Figure taken from Reuter-Lorenz and Park (2014:360).

The STAC-r proposes that cognitive performance is preserved by means of compensatory brain processes. The key element is compensatory scaffolding (CS). The authors maintain that convincing evidence for CS comes from studies showing increased regional brain activity in older adults, compared to younger adults, as well as bilateral activation but not unilateral activation when performing a task. It is not fully clear, however, whether this means compensation (for a review, see Grady, 2012). The CS incorporates both life course factors (experience and states from birth to death) and life span (ageing), that influence the structure and function of the ageing brain, and also directly affect the development of CS. The life course factors are divided into positive factors (neural resource enrichment) and negative factors (neural resource depletion) that influence the ageing process of cognitive function.

The positive factors include those previously mentioned with regard to CR, such as bilingualism and multilingualism, and have been shown to attenuate age-related cognitive decline, and delay the onset of AD. These can have direct, enhancing or preserving effects on brain structure and function. The positive factors can also exert indirect effects on brain structure and function by increasing the capacity for CS and consequently attenuating the process of cognitive decline.

The negative life course factors, exert, as the name suggests, negative effects on brain structure and function, and, in turn, have depletion effects on cognition. These effects include dementia type risk factors, such as the presence of the APOE-4 gene, which is thought to substantially increase the risk of AD (Slooter et al., 1998), and the presence of amyloid and tau deposition associated with AD (Rodrigue et al., 2009). Other factors include stress (McCune, 2007), which has been suggested to play a role in the loss of hippocampal mass, as a result of hyper-secretion of cortisol (McCune, 2007).

Lastly, the STAC-r also incorporates the potential beneficial effects of (formal and structured) interventions, such as cognitive training, which has gathered a large amount of interest lately. A meta-analysis from RCTs (Valenzuela and Sachdev, 2009) demonstrates the beneficial effects of cognitive training. They investigated the effect of cognitive exercise on longitudinal cognitive performance in healthy older adults. The reviewed studies included interventions such as reasoning training and information processing, speed, memory, and problem solving training. Valenzuela and Sachdev (2009) reported a strong positive effect of cognitive exercise on cognitive performance, with the data also suggesting that two to three months of cognitive exercise may result in long-lasting and tenacious effects on cognitive performance in the healthy elderly. This will be looked at in Chapter 11.

This section has introduced three models of compensation mechanisms, BR, CR, and STAC-r. STAC-r offers similar concepts to BR and CR, and can be thought of as a more comprehensive and flexible edition of these two concepts, in one model. Furthermore, the STAC-r does not only focus on older adults, but is rather seen as a life course model, which is important as there is increasing interest in other age-groups than the oldest adults in the cognitive ageing literature; this applies, for example, to middle aged individuals (Karlamangla et al., 2014). The concept CR will be used for the purpose of this thesis, with reference to both CR and its similar concept in the STAC-r model.

2.6 CR, bilingualism and multilingualism

Recent longitudinal evidence suggests that speaking two or more languages influences cognitive ageing. Controlling for childhood intelligence, Bak et al. (2014) reported positive influence of bilingualism on later-life cognition. Moreover, accumulating evidence indicates that speaking two or more languages regularly may be one factor contributing to CR, and subsequently delaying the onset of pre-clinical MCI and clinical symptoms of dementia (for example Bialystok et al., 2014; Alladi et at., 2013; Ossher et al., 2013; Schweizer et al., 2012; Gollan et al., 2011; Chertkow et al., 2010; Craik et al., 2010; Bialystok et al., 2007).

As will be introduced in Chapter 4, there is evidence to suggest that compared to monolinguals, bilinguals have enhanced cognitive control, which in turn strengthens and reorganises their neural networks. It has been proposed that this cognitive “exercise”, and its associated structural and functional alterations, contribute to CR (see Guzmán-Vélez and Tranel, 2015, for a recent review). However, as this chapter has shown, it is also clear that individual differences play a role in the development of cognitive reserve. Thus, this would be similar to other factors which have been proposed as potential CR indicators, such as engaging in cognitive stimulating activities (Wilson et al., 2013; Reed et al., 2011; Lachman et al., 2010; Plassman et al., 2010; Stern, 2009; Sing-Manoux et al., 2003). The following sub-sections detail these exciting findings regarding bilingualism and multilingualism, central to the hypotheses of this thesis, which investigates the proposed underlying mechanisms of bilingualism as a contributor to CR; whether compared to bilingualism, trilingualism means greater cognitive control, hence greater CR.

2.6.1 Bilingualism, CR and AD

2.6.1.1 Neuroimaging evidence

Convincing neuroimaging evidence for bilingualism contributing to CR comes from a study by Schweizer and colleagues (2012), who explored the structural differences between monolinguals and bilinguals, cognitive function, and AD. Schweizer et al. (2012) examined 20 monolinguals and 20 bilinguals, who had been diagnosed with probable AD. The two groups were matched for cognitive ability (Behavioural Neurology Assessment test of cognitive function, which measures attention, memory, visuospatial function, language and naming), plus EF and education, but the monolinguals had significantly higher occupational status. A computerised tomography (CT) scan revealed significantly more medial temporal lobe atrophy in the bilinguals' brains, compared to monolinguals. Thus, although the bilinguals' brains had suffered more neuropathological atrophy than those of the monolinguals, their cognitive ability was equal. This indicates that bilinguals have greater cognitive reserve than monolinguals, which enables them to function comparably, despite suffering more neuropathological atrophy. This finding is promising, but yet needs replication, and further investigation. For instance, it is still unclear exactly how much atrophy bilinguals can suffer before showing clinical symptoms of dementia, although this would be difficult to determine due to individual differences.

Moreover, there is also evidence to suggest that lifelong practice of speaking two languages contributes to reserve against both white matter and grey matter density age-related declines, commonly in areas associated with cognitive control (Abutalebi et al., 2015; Olsen et al., 2015; Luk et al., 2011a). For example, Abutalebi and colleagues (2015) reported increased grey matter density in both left and right inferior parietal lobules of older bilinguals, compared to their monolingual counterparts. Luk et al. (2011a) reported increased white matter connectivity in older bilinguals, compared to monolinguals. This was largely seen in the corpus callosum, which connects the left and right frontal cortices, as well as increased anterior to posterior connectivity. Similar effects were observed in young bilinguals, who acquired their L2 later in life but have actively used both languages (Pliatsikas et al. 2014), suggesting that experience-related changes do not require a long time to manifest. Indeed, similar results have been shown after short term (6 weeks) training of pseudo words – see Chapter 4. Lastly, a very recent study (Olsen et al., 2015) observed increased white matter volumes in the frontal lobe of bilinguals, compared to monolinguals. Additionally, Stroop task performance (inhibitory control) was significantly associated with frontal lobe white matter volume, although this did not significantly differ between the language groups. They also observed that the temporal lobe cortical thickness was attenuated with age in bilinguals, but not monolinguals.

These findings certainly indicate that bilingualism has a positive experience-related impact on the brain, particularly in regions associated with cognitive control (frontal lobes). However, these effects do not always transfer to behavioural performance. For example, Olsen et al. (2015) applied the Stroop task, and several other cognitive tasks, such as Mini-Mental State, fluency tasks and a Trail-making task, but similar performance was observed on all, even though bilinguals showed increased white matter volumes in the frontal regions, compared to monolinguals.

2.6.1.2 Age of onset of symptoms of dementia and bilingualism

The first study to examine whether bilingualism delays the onset of dementia was carried out by Bialystok and colleagues (2007). This retrospective study (data collected from medical records) comprised 184 patients who met the criteria for probable dementia. These patients were divided into 91 monolinguals and 93 bilinguals with 25 different languages. Most of the patients were immigrants, however, this did not affect the age for symptom onset or diagnosis. The criteria for bilingualism were that they had spent most of their lives regularly using at least two languages. Compared to bilinguals, monolinguals had spent significantly more years in education, and had a higher occupational status. The two language groups scored similarly on the mini-mental state exam (MMSE), which was administered at the patients' initial clinic visit. Bialystok et al. (2007) found that the mean age for onset of symptoms of dementia was 71.4 among monolinguals and 75.5 among bilinguals and this was significantly different (mean difference = 4.1 years), and this was not accounted for by education or occupational status. Although this study is not faultless, for example, time at onset of symptoms was estimated by family, it strongly indicates that bilingualism can be considered as CR. Also, it should be noted that as MMSE does not directly test EFs it cannot be concluded that the reported delay among bilinguals is due to enhanced EF. Furthermore, in the early stages of AD memory functions are mainly affected due to damage to the medial temporal lobe, not executive functions (Gold, 2015). However, as the finding by Schweizer et al. (2012) suggests (see section 2.6.1.1), bilinguals seem to better tolerate damage to the medial temporal lobe than monolinguals. That is, they perform similarly on EF tests, despite having more neuropathological atrophy in the medial temporal lobe.

Two more studies from Bialystok's lab replicated these findings. Craik et al.'s (2010) study consisted of 211 patients (102 bilinguals and 109 monolinguals), 97 of which were immigrants, although there was no effect of immigration on age of symptom onset or diagnosis of AD only. As in the first study, education and occupational status were controlled for, and importantly monolinguals had spent more years in education. No significant difference was found on the MMSE at the patients' first clinic visit. The results showed that both the age of onset of AD symptoms and diagnosis significantly differed between language groups (age of onset = 72.6 in monolinguals and 77.7 in bilinguals (mean difference 5.1 years). More recently, further support was provided by Bialystok et al. (2014), where the bilingual patients showed onset age of AD 7.3 years later than monolinguals. Both of these effects were independent of several potential confounding factors (diet, alcohol, smoking, physical and social activity).

Bilingualism delaying the symptom onset of dementia has also been confirmed in India, which is known for linguistic diversity and where immigrant status is not associated with bilingualism (Alladi et al., 2013). The sample consisted of 648 patients (257 monolinguals, 391 bilinguals, trilinguals and quadrilinguals, and individuals who spoke more than four languages. Although, the sample consisted of many language groups, the authors grouped all individuals who spoke two or more languages into a "bilingual" cohort. There were no statistical differences between two, three or four languages in terms of the age at onset of dementia, which is presumably the reason they were all referred to as "bilinguals".

This is something that this thesis seeks to clarify. That is, whether researchers need to be more specific when allocating to language groups, to avoid possible confounding effects from other language groups. Similarly, whether researchers need to be more specific regarding the labels they choose for their respective language groups. For example, would it have been more appropriate if Alladi and colleagues (2013) had referred to the "bilinguals" as what they really were? I.e., "multilinguals". This needs clarification – especially considering the rate at which the bilingualism and cognition literature is going, and if there is evidence to suggest that trilinguals' cognitive abilities, such as EF, are significantly different from that of bilinguals' – See Chapters 5 and 12, for a discussion of this.

Alladi et al. (2013) reported that compared to monolinguals, bilinguals were 4.5 years older at onset of dementia symptoms (monolinguals' mean age = 61.1 years, bilinguals' mean age = 65.6 years). Additionally, when the subgroups of dementia were examined it was observed that bilingualism delayed onset of symptoms of AD by 3.2 years, by six years with frontotemporal dementia and 3.7 years with vascular dementia. Several potential confounding factors were examined (such as literacy and education) but none interacted with bilingualism. Interestingly, compared to monolinguals, illiterate bilinguals still showed a delay of six years of age of onset of dementia (overall).

The cross-sectional evidence presented here for bilingualism contributing to CR and delaying dementia, is promising. However, this positive effect of bilingualism is not always replicated. For example, a longitudinal, community-based study investigated bilingualism, cognitive decline, and dementia (Zahodne et al., 2014). The sample consisted of 1,067 individuals, 430 immigrant bilinguals and 637 monolinguals, which were followed up to 23 years. The age at baseline was approximately 75 years for bilinguals and 76 years for monolinguals. The results suggest that, independent of education, age, and time spent in the L2 country, bilingualism does not protect against age-related cognitive decline, or the risk of dementia. Similarly, another community based study (Yeung et al., 2014), which both used cross-sectional and longitudinal analyses (sample size = 1,616), did not observe any protective effects of bilingualism regarding dementia, nor was it associated with higher cognitive ability or change.

Sometimes this protective effect may dependent on other factors. For instance, Chertkow et al. (2010) only observed delayed onset of symptoms and diagnosis of AD in immigrant bilinguals. Furthermore, Gollan et al. (2011) found that the delayed onset of AD was only seen in bilinguals with low educational level (as opposed to high), and as the bilinguals' language proficiency level increased, the later was the age of diagnosis. It is therefore evident that this is tricky to study.

2.6.2 Bilingualism, CR and MCI

The protective effects of bilingualism have also been extended to pre-clinical dementia (MCI) (Bialystok et al., 2014; Ossher et al., 2013; Perquin et al., 2013). For example, Ossher et al. (2013) investigated this in older (mean age = 75.5 years) monolingual and bilingual participants, who were divided into subgroups which were (i); single domain amnestic MCI (49 monolinguals and 19 bilinguals) and (ii) multiple domain amnestic MCI (22 monolinguals and 21 bilinguals). Education did not differ between the language groups. The reported duration of impaired cognitive symptoms prior to study did not differ between the language groups, for either domain group (mean = 2.5 years). However, at the age of testing, bilinguals were significantly older than monolinguals in the single domain group (mean difference = 4.5 years), but no age differences were observed for the multiple domain group. The patients completed a battery of neuropsychological tests. The language groups did not differ in performance on any of the tests in the single domain group. The bilinguals in the multiple domain group were, however, slower to name colour squares in the Stroop task. Ossher and colleagues (2013) observed no differences in terms of age of diagnosis between the two language groups for the multiple domain aMCI, but bilinguals in the single domain MCI were diagnosed significantly later (mean = 4.5 years) than their monolingual counterparts. It is unclear why this protective effect was only seen in single domain aMCI. The authors speculated that this may be because of the observation that multiple domain aMCI is associated with more frontal lobe pathology than single domain aMCI (Bell-McGinty et al., 2005), and therefore the bilinguals with multiple domain aMCI were unable to use compensatory mechanisms in the frontal lobe area, as that is the area of impairment.

Another recent study (Bialystok et al., 2014), which also examined AD (see sub-section 2.6.1), found evidence of bilingualism delaying the onset of MCI symptoms, although they did not subdivide MCI. Monolinguals and bilinguals did not differ in cognitive ability at their first clinic visit. The bilingual participants showed onset age of MCI 4.7 years later than monolinguals, and this was independent of diet, alcohol, smoking, physical and social activity. Lastly, Perquin et al. (2013) also showed supportive evidence for this, although their sample only included multilinguals, who spoke two to seven languages (see sub-section 2.6.3).

2.6.3 More languages, greater CR?

Some studies suggest that the number of languages spoken is an important factor regarding CR, and more than two languages are sometimes needed to achieve the protective effect. The results of Chertkow et al. (2010) indicate no benefit of being bilingual on age of AD onset, unless in a pure immigrant sample. Interestingly, Chertkow and colleagues (2010) observed a small, but significant, protective effect of speaking three or more languages. This was seen both overall, and when the groups were subdivided into immigrants and non-immigrants, suggesting that immigrant status is perhaps less important when one speaks more than two languages.

This potential protective effect of speaking three or more languages is in line with findings from individuals who are either healthy, or in pre-clinical stages of dementia. Kavé and colleagues (2008) compared performance of presumably healthy (authors did not make it clear) elderly (mean age = 83 years) bilinguals, trilinguals and multilinguals on two cognitive screening tests [Mini Mental State Examination (MMSE) and Short Orientation Memory Concentration Test (OMCT)]. They found that cognitive state was significantly higher in trilinguals compared to bilinguals, and in multilinguals compared to trilinguals. Furthermore, Perquin et al. (2013) studied the potential protective effect of multilingualism against cognitive impairment in an elderly cohort, as well as whether the time of acquisition would be an important factor. They tested 232 participants without dementia, dividing them into two groups; MCI group and no MCI group. The authors refer to MCI as ‘cognitive impairment no dementia’ (CIND) and explain it as individuals who do not meet the criteria for dementia but show a noticeable decline in cognitive abilities, which does not affect their daily functioning. As MCI and CIND seem to be two different labels of the same construct MCI will be used here. Perquin et al.'s (2013) findings indicate a protective effect against MCI among multilinguals who actively practised their languages. Importantly, this effect is observed in a non-immigrant sample. Further to this, it was found that the earlier and more rapid acquisition of multilingualism, the more protection was noted. Interestingly, compared to bilinguals, individuals who spoke more than two languages were observed to have lower risk of an MCI diagnosis. This effect remained after holding age and education constant. However, this multilingualism protective effect was not found by Alladi et al. (2013), as no statistical difference was found between individuals who spoke, two, three, four or more languages.

Although a limited number of studies have investigated the “more languages, greater reserve” hypothesis, their findings suggest that this is indeed the case. Whether this is due to trilinguals’ enhanced cognitive control is the central hypothesis of this thesis. Kavé and colleagues‘ (2008) finding of greater general cognitive ability with increasing number of languages indicates that this may also be the case regarding cognitive control.

2.7 Chapter summary

This chapter has introduced the literature on healthy cognitive ageing, MCI and dementia, and how onset of MCI and dementia (and its sub types) can be delayed by the means of compensatory mechanisms, such as CR and BR. The chapter has also introduced the literature supporting (and counteracting) bilingualism as a contributing factor to CR, delaying the onset of clinical expression of AD up to seven years and MCI four years. The impact of number of languages on the protective effect of CR was also presented. The limited evidence on multilingualism suggests that with more languages multilinguals speak the less risk they are of being diagnosed with MCI, and to more likely to maintain general cognitive ability with ageing. This indicates this is also the case with cognitive control.

Chapter 3: Executive function

3.1 Introduction

The previous chapter provided an overview of the literature on normal cognitive ageing, dementia, CR and concluded with recent studies that have provided evidence that speaking two or more languages may be a possible factor contributing to cognitive reserve. The present chapter introduces executive function (EF), in particular cognitive control. EF and cognitive control are often used interchangeably in the literature. For the purpose of this thesis EF is seen as a broader definition, which encompasses both neuropsychological and cognitive aspects of EF, whereas cognitive control is seen as a narrower definition, focusing on cognition. As can be seen in Chapter 4, cognitive control has been studied widely in the bilingualism and cognition literature, and its deeper concepts will now be introduced.

3.2 Defining EF

It has been argued that the EF construct, and what it involves, is elusive, and therefore difficult to define (Barkley, 2012; Banich, 2009; Jurado and Rosselli, 2007). Various components have been suggested to fall under the umbrella of EF. These include goal setting, inhibition, initiation of activity, monitoring, planning, problem solving, self-regulation, shifting and WM (Barkley, 2012). An example of the elusiveness of EF is the debate as to whether EF should be viewed as a unitary construct – such as Norman and Shallice's "Supervisory Attentional System" (SAS) (1986) – or several distinct functions. After decades of speculation and wealth of research (some of which is mentioned in section 3.4), many researchers are now coming to the conclusion that EF is a complex and multidimensional phenomenon, consisting of three core processes, namely inhibition, WM updating and shifting, that are independent but yet related

(Miyake and Friedman, 2012; Banich, 2009; Friedman et al., 2008; Miyake et al., 2000). Consequently, and also because EF involves processes outside EF, it is very difficult, and potentially impossible, to design a pure EF task, which only measures one particular function (Miyake and Friedman, 2012; Friedman et al., 2008).

Different fields focus on different aspects of EF, and definitions therefore depend on which aspect/level is being assessed. In neuropsychology, definitions are often based on observed post brain insult behaviours, whereas in the field of cognitive neuroscience, the definitions seem to be more specific, and often rest on unseen behaviour; cognition. The definition provided by Snyder et al. (2015:1) captures the essence of both fields, they define EF as *"a set of cognitive control processes … which regulate lower level processes (e.g., perception, motor responses) and thereby enable self-regulation and self-directed behaviour toward a goal, allowing us to break out of habits, make decisions and evaluate risks, plan for the future, prioritize and sequence our actions, and cope with novel situations"*. Cognitive control is the aspect of EF that will be focused on in this thesis. As Snyder et al.'s (2015) definition indicates, cognitive control processes are, for humans, the key to fully functioning beyond the level of simply avoiding predators, gathering food and reproduce.

3.3 The importance of studying EF/cognitive control

The importance of cognitive control becomes obvious when its underlying processes do not work as they should. Impairments of EFs, such as inhibitory control deficits, have been implicated in disorders such as attention deficit and hyperactivity disorder (van Velzen et al., 2014), autism spectrum disorder (Kenworthy et al., 2008), obsessive-compulsive disorder (van Velzen et al., 2014), depression (Snyder, 2013), schizophrenia (Barch and Ceaser, 2012), and drug and alcohol addictions (Wilcox et al., 2014; Baler and Volkow, 2006). It has also been suggested that when we are faced with some mentally draining difficulties, for example psychological stress (Liston et al., 2009) and sleep deprivation (Killgore, 2010), or are physically unfit (Hillman et al., 2008) EF problems can result with symptoms similar to those associated with EF disorders (Diamond, 2013). Even suffering from tinnitus, the phantom ringing in the head/ears, has been associated with reduced inhibitory control (Heeren et al., 2014).

Conversely, in the context of neuroplasticity – the brain´s ability to structurally and functionally change in response to environmental demands (Chang, 2014) – cognitive control can also be enhanced as a result of cognitive “exercise“ (see Chapter 2), such as managing more than one language; hence cognitive reserve. Thus, studying cognitive control in this context is imperative, as it has become increasingly important to maintain sucessful ageing for as long as possible. Before introducing cognitive control, and its sub-processes (see section 3.5 and onwards), the following section will introduce the link between EFs and the brain.

3.4 EF and the brain

EF has been described as being mostly mediated by the prefrontal cortex (PFC), although other areas of the brain have also been implicated (see next three sub-sections). The PFC is located anterior to the motor and premotor cortices on the surface of the frontal lobes, and according to Szczepanski and Knight (2014), the main PFC subdivisions are dorsolateral, dorsomedial, ventrolateral, ventromedial, rostal and orbitofrontal. The anterior cingulate, the left and right inferior parietal lobules, and frontal lobes, have been implicated in bilingualism (Abutalebi et al., 2015; Luk et al., 2011a; Mechelli et al., 2004), as well as subcortical structures, such as the caudate (Zou et al., 2012) and the putamen (Abutalebi et al., 2013).

Other functions than EFs have been proposed to be mediated by the frontal lobes. Drawing on patient studies Stuss and colleagues (for a recent review, see Stuss, 2011), suggest that including EFs there are at least four functions of the frontal lobes; energization, emotion/behavioural regulation and metacognition. Language processing has also been associated with this area, including the inferior frontal gyrus, where the Broca's area is situated (Friederici, 2011), usually in the left hemisphere, the more dominant hemisphere for language (Toga and Thompson, 2003). Patients with lesions in the prefrontal cortex often have difficulties with tasks depending on EF. For example, the dorsolateral PFC has been shown to be essential for WM (measured by the N-back task), namely for monitoring and manipulating the content of it (Barbey et al., 2013; Tsuchida and Fellows, 2009). Patients with ventrolateral PFC lesions have been shown to have difficulties with inhibitory control (Hamilton and Martin, 2005; Aron et al., 2003). Further evidence that EFs are mediated from the PFC comes from a recent meta-analysis of structural neuroimaging studies (Yuan and Raz, 2014). Basing their hypothesis on the "bigger is better" view, Yuan and Raz (2014) examined the relationship between EFs and the size of the prefrontal cortex (PFC). Their analysis of 3,272 healthy adults showed that better performance on tests, such as Wisconsin Card Sorting Test (WCST), digit backwards span (WM), verbal fluency and Trail Making Test, was associated with both larger PFC volume, and greater cortical thickness, and this link was particularly robust in the lateral area of the PFC. The tests did however vary in terms of the strength of the association with PFC volume, with the WCST showing the strongest link, and verbal fluency showing no link.

However, the brain and behaviour relationship is highly complex (Alvarez and Emroy, 2006), and evidence from patient focal lesion studies suggests that EFs are not only mediated by the PFC, but other areas too, such as sub-cortical (for reviews, see Szczepanski and Knight, 2014; Stuss and Levine, 2002). Furthermore, cumulative functional neuroimaging evidence also suggests that EFs, and other cognitive functions, are not only limited to the PFC but are mediated by several areas of the brain, and form complex functional networks (Niendam et al., 2012; Collette et al., 2006; Cabeza and Nyberg, 2000). A recent meta-analyses investigated this in terms of EF, in healthy, 18 to 60 years old individuals Niendam et al., 2012). Niendam and colleagues analysed 193 fMRI studies, looking at brain activation and EF performance, particularly processes linked to cognitive control (inhibition, WM, flexibility, initiation, planning and vigilance). They performed a global analysis across all domains, and a domain specific analysis, concentrating on inhibition, WM and flexibility. The global analysis revealed a shared pattern of activation in areas including the prefrontal PFC, frontopolar cortex, orbitofrontal cortex, anterior cingulate, parietal, temporal and occipital areas, and subcortical areas (caudate, putamen, thalamus and cerebellum). The authors proposed that this suggests that EFs are sustained by a shared superordinate cognitive control network. The domain specific analysis revealed some shared activation for inhibition, WM and flexibility (for instance in the dorsolateral PFC, parietal, temporal and occipital areas), but also domain specific areas. For example inhibition, but not the others, significantly activated the anterior cingulate cortex, and WM and flexibility the cingulate. Also, subcortical areas were activated by inhibition and WM, but not flexibility.

3.5 Cognitive control

There is a limit to the amount of information our cognitive system can process from the environment at any given time. Consequently, we are forced to be selective in terms of what we take in, and thus we are inclined to process only the information that is relevant to our current goals (Lachter et al., 2004). Without this kind of cognitive control it would be difficult to make sense of, and process, the information we are constantly bombarded with.

Evidence indicates that cognitive control is mediated by the dorsal anterior cortex and dorsolateral prefrontal cortex (Carter and van Veen, 2007). Most models agree on the core processes involved in cognitive control, but often use different terms to describe these processes. Diamond (2013) posited that the core components of EF are inhibition, WM and cognitive flexibility, and that from these components higher-order EFs are built (reasoning, problem solving and planning). Similarly, Miyake et al.'s (2000) model, which is widely cited in the bilingualism and cognitive control literature, suggests inhibition, WM updating and shifting to be the core components of EF. Inhibition and WM updating will be discussed in more detail below as they are central to this thesis. Shifting is the ability to switch between mental tasks, such as writing a research paper and attending to your children's needs (also referred to as task-switching) (Miyake, 2000). Diamond's (2013) "flexibility" appears to be a broader definition of Miyake et al.'s (2000) "shifting" component, reflecting that Diamond's model comes from a neuropsychological perspective, and Miyake et al.'s (2000) more from a cognitive perspective.

In 2012, Miyake and Friedman updated their model, the "unitiy/diversity framework", based on their twin study (Friedman et al., 2011) and other studies of theirs (e.g., Friedman et al., 2008) and from other labs, showing similar pattern of unity/diversity. This updated model proposes two separate components – WM updating and shifting – and a common component consisting of these two, inhibition. That is, inhibition is not seen as separable from WM updating and shifting, as Miyake and colleagues observed no unique variance of inhibition, and was it thus inseparable from the common factor (Friedman et al., 2011; 2008). So, tasks that are thought to tap inhibition, tax a common EF factor, which should then be observed across all EF tasks, and is this separable from WM updating and shifting. See Figure 2.

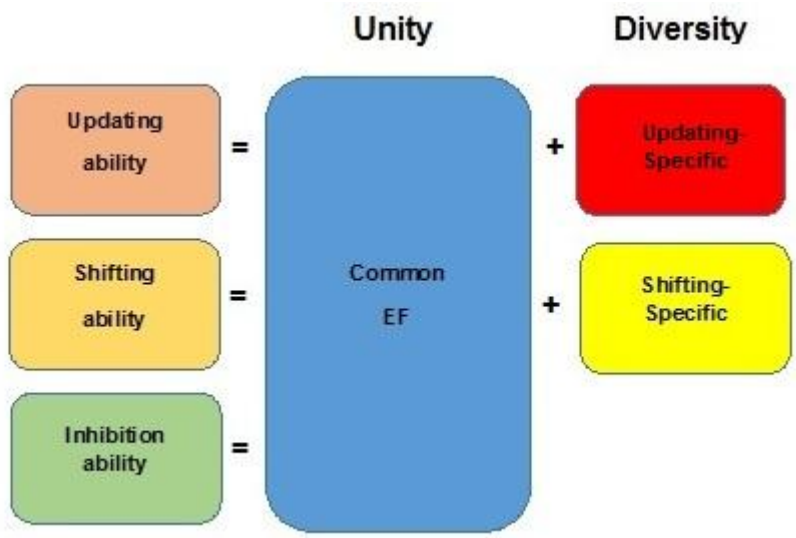

Figure 2. A simplified schematic diagram of the unity and diversity model (adapted from Miyake and Friedman (2012)).

Miyake and Friedman (2012) proposed that this common factor (unity) reflects active goal maintenance which they define as the *"ability to actively maintain task goals and goal-related information and use this information to effectively bias lower-level processing"* (p.11), and it is this ability that is required for all three functions (Miyake and Friedman, 2012). Additionally, it has been proposed that goal maintenance is a crucial requirement of response inhibition (Munakata et al., 2011). Perhaps this common factor could then simply be inhibition, and is therefore the underlying mechanism for both WM updating and shifting Valian (2015).

A closely related concept to cognitive control is conflict monitoring, also referred to as attentional monitoring, or monitoring. This is one of the functions that has been positively implicated in bilingualism, and the remaining sections of this chapter introduce this concept, as well as inhibition and WM, all of which will be assessed in this thesis.

3.6 Inhibition

The term inhibition has a broad meaning, depending on the level of analysis, ranging from neural inhibition to behavioural inhibition. A broad definition of this construct can be *"the ability to supress stimuli, responses or impulses, behavioural alternatives, overlearned habits, interpretations, and memories that are currently irrelevant, interfering, incorrect, or inappropriate to perform goal-directed behaviour"* (Enge et al., 2014:988). At a psychological level this can be explained as the ability to resist telling your mother that her cooking is less than mediocre (i.e., supressing your impulse). Without this ability we would be impulsive and slaves of old habits, of both thought and action (Diamond, 2013).

At the level of cognition, inhibition can been defined as the ability to control (suppress or ignore) task-irrelevant information (Friedman and Miyake, 2012; MacLeod, 2007). Put simply, it is the act of tuning out information that is not relevant to us at a particular time point, and thus helps filtering out irrelevant information or stimuli we are constantly bombarded with. It is thought that inhibition occurs both consciously (controlled and goal-driven) and non-consciously (automatically). Controlled inhibition is the type considered to be one of the components of EF, and includes supressing irrelevant information and inhibiting prepotent responses (Friedman and Miyake, 2012; MacLeod, 2007). For instance, bilinguals use this type of inhibition when they need to supress/ignore words in their first language (L1) whilst conversing in their second language (L2). This type of inhibition will be looked at in Chapters 5 and 8. An example of automatic inhibition is "inhibition of return" (IOR), which will be looked at in Chapter 7. It has been suggested that this mechanism reflects a bias against returning attention to previously attended locations, by suspending both motor responses (eye movements) and the return of attention, which increases the efficiency of visual search in the environment, with the aim of not wasting attentional resources (Wang et al., 2013; Tian et al., 2011; MacDonald et al., 2009; Klein, 2000).

The IOR task, the Stroop task (Stroop, 1935), the Simon task (Simon and Small, 1969) (see detailed descriptions in Chapters 7, 8 and 5), the Flanker task (Eriksen and Eriksen, 1974) and the Stop Signal task (Logan, 1994) are all thought to tap into inhibition. This list is not exclusive. Although all these are similar in the sense that they all create conflict, where irrelevant stimuli must be ignored or suppressed, they are thought to tap into different types of inhibition. However, there is also evidence that they share an underlying mechanism (e.g., Wang et al., 2013; Ivanoff and Klein, 2002; Vivas and Fuentes, 2001).

3.7 Monitoring

A closely related concept to cognitive control is conflict monitoring, which as stated above is also referred to as attentional control, attentional monitoring or monitoring. For the purpose of this thesis it will be referred to as monitoring. The conflict monitoring framework posits that there is a system that monitors information processing, with the purpose of determining whether there are any likely conflicts that need to be dealt with (Botvinick et al., 2004; 2001). This system evaluates present levels of conflict and whether application of cognitive control, such as inhibition, is needed (Botvinick et al., 2001). In the case of bilinguals, monitoring has been proposed to help determine which language should be spoken, and in what context and to decide whether cognitive control needs to be applied in order to either continue to speak in the chosen language, or whether to switch to the other language (Costa and Sebastián-Gallés, 2014).

The same tasks used to asses inhibitory control, such as the Stroop task (Stroop, 1935) and the Simon task (Simon and Small, 1969), measure monitoring. The overall reaction time on these tasks (congruent and incongruent trials) is taken as a measure of monitoring. In the Simon task (see Chapter 5, section 5.1.2 for a detailed description), participants are presented with different coloured squares (such as blue and red) on either side of the screen, and are instructed to press, for example, the left button when they see the red square, and the right button when they see the blue square. On congruent trials the square and the response correspond (e.g., red square presented on left side of the screen and the left button is pressed). On incongruent trials the square and response do not correspond (e.g., red square is presented on the right side of the screen and the left button should be pressed). Incongruent trials thus create conflict as the prepotent response is to press the right button. Like cognitive control, monitoring is thought to be mediated by the dorsal anterior cortex and the dorsolateral prefrontal cortex (Carter and van Veen, 2007). The Simon task is used in Chapter 5 of this thesis, for investigation of trilingualism and monitoring/inhibitory control.

3.8 WM

As inhibitory control, WM has important implications for health and ageing (ageing for both functions will be looked at in experimental chapters), and is for instance seen as one of the cognitive deficits in schizophrenia (Barch and Ceaser, 2012; Barch, 2005).

It is commonly thought that WM, which is thought to have limited capacity, involves processes such as maintaining, manipulating and updating relevant information in short-term memory, and that these operations allow the limited information we can handle, to be temporarily accessible, for an on-going cognitive task (Baddeley, 2003).

Some researchers view WM as mostly synonymous with EFs (e.g., McCabe et al., 2010; Engle and Kane, 2004) and is this common mechanisms referred to as “executive attention” by McCabe et al. (2010) and “controlled attention” by Engle and Kane (2004). Engle and Kane (2004) proposed a controlled attention framework, in which WM capacity is related to attention control, and individual differences in inhibitory control may determine individual differences in WM capacity (Engle and Kane, 2004). Others view WM as a subcomponent of cognitive control (or EFs). Baddeley and Hitch (1974) proposed a three component model, which assumed a limited capacity controller (central executive) which is supported by two temporary storage systems (slave systems), namely the phonological loop and the visuo-spatial sketchpad. Information is phonologically coded in WM by the phonological loop and with the visuospatial sketchpad, information is visually coded in WM. The central executive is thought to control these two subordinate systems by retrieving information from memory, identifying task goals, initiating response and so on. More recently, Baddeley (2000) proposed the fourth component; the episodic buffer. The episodic buffer is thought to be controlled by the central executive, and to be a short term multidimensional store, providing a temporary interface between the phonological loop and the visuospatial sketchpad, and long-term memory. It is thought to play a central role in the binding of features into objects.

As seen above – according to the unity/diversity framework WM and inhibitory control share a common underlying mechanism (Miyake and Friedman, 2012), or WM relies on inhibition Valian (2015) – the proposed bilingual advantage in inhibitory control should then be transferred to WM capacity. Bilinguals, thus, may rely on WM whilst monitoring their speech, and deciding which language to use, and whether they need to supress intrusive words from the language they are not currently using. As will be looked at in Chapter 4, the bilingual advantage has been observed in both verbal and non-verbal episodic memory, which is not surprising, considering that episodic memory has been strongly linked to "executive attention" (McCabe et al., 2010). Consequently, one can assume as "executive attention" consists of both WM and inhibitory control, that bilingual advantage is also seen in WM.

Tasks thought to tap WM are the N-back task (Kirchner, 1958) (see Chapter 6 for a detailed description), Corsi Block test (Corsi, 1972), Self-ordered pointing task (Petrides et al., 1993), and digit span tasks (forward, backward and complex). In the Corsi Block test, the participant is to touch a series of blocks in the same order as the tester previously did. In the self-ordered pointing task, the participant is presented with a set of stimuli, and is required to point to all, but only one stimulus at a time, without pointing to a stimulus that has been pointed to before. Both forward digit and backward digit span tasks are often used to measure WM. However, not all researchers agree that the forward digit span task taps WM. In this task participants are required to repeat back items, such as numbers or letters, in the order in which they were told. It has been argued that as it only requires that information is held in mind it is simply a measure of short term memory (Diamond, 2013).

3.9 Chapter summary

This chapter gave a review of EF, centring on the cognitive control processes, inhibition, monitoring and WM. These have been implicated in the bilingualism and cognition literature, and this thesis provides in depth investigations into the effects of trilingualism on EFs; Chapters 5, 7 and 8 look at inhibitory control/monitoring utilising the Simon task, IOR task and the Stroop task. These tasks, in particular the Simon task and Stroop tasks, have been widely used comparing bilinguals and monolinguals' performance, and therefore it seems logical to assess trilinguals' performance on these too. Chapter 6 looks at WM, using the N-back task, and in Chapter 9, both the Simon task and N-back tasks are looked at more closely. The N-back task was chosen as it is thought to tap WM updating (Friedman et al., 2011; Miyake et al., 2000), something that previous, limited studies comparing bilinguals and monolinguals, which mainly used memory span tasks, have not investigated regarding WM.

Chapter 4: Bilingualism and cognition

4.1 Introduction

Now that cognitive reserve and cognitive control have been considered, this final introductory chapter aims to provide a general initiation to the cognitive consequences of bilingualism. The chapter will provide an overview of literature on how bilingualism affects cognition in general, in language control, and the proposed underlying mechanism as to why, compared to monolinguals, bilinguals/multilinguals demonstrate more cognitive reserve i.e., enhanced cognitive control. This chapter will also address the recent literature which has shown similar performance between monolinguals and bilinguals, and studies that have shown a bilingual disadvantage. This chapter will then conclude by considering whether trilingualism provides greater enhancement of cognitive control.

4.2 Cognitive consequences of bilingualism

The context for exploring how bilingualism affects cognitive control is neuroplasticity. Researchers have reported effects of neuroplasticity on brain structure and function (Chang, 2014). Longitudinal studies have shown experience-related structural plasticity following training, such as after three months of juggling training (Draganski et al., 2004), or three years of taxi-driving training (Woollett and Maguire (2011). As this thesis has indicated thus far (see Chapter 2), bilingualism can be viewed as an experience resulting in neuroplasticity. Chapter 2 then showed that language experience with L2 results in substantial neuroplasticity, both in terms of increased white and grey matter, in older bilinguals with lifelong bilingual experience, and in young late L2 bilinguals (Abutalebi et al., 2015; Olsen et al., 2015; Schweizer et al., 2012; Luk et al., 2011a). Previously, increased grey matter density was observed in the left inferior parietal lobule in bilinguals over monolinguals (Mechelli et al., 2004), and this was especially pronounced in early and very proficient bilinguals. This indicates, at least in terms of brain structure, that the “exercise” of speaking two languages may contribute to attenuation of age-related changes, and that these experience-related changes also occur in bilinguals who start acquiring L2 later than childhood.

An interesting recent strand of research further supports the notion that the experience-related benefits of speaking two languages do not have to start in early childhood to have meaningful effects. On the contrary, compared to controls, plasticity has even been shown in young adult L2 learners, following only a short period of language training (e.g., Hosoda et al., 2013; Schlegel et al., 2012). For instance, Schlegel et al. (2012) collected monthly diffusion tensor imaging scans during and after nine months of intensive L2 training (7.5 hours per week), and reported structural white matter changes within areas that have been associated with language processing (e.g., between frontal cortical hemispheres and the caudate), as well as others. They also observed a significant positive correlation between the degree of white matter changes and how successful individuals were at language learning. Also, Hosoda et al., (2013) reported that after only four months’ training of learning L2 words, the L2 learners showed increased density of both grey and white matter in the right inferior frontal gyrus, and these changes were positively associated with their knowledge of the L2 vocabulary. A justifiable question would then be whether these changes transfer to enhanced cognitive control. Findings by Linck et al. (2008) (see Chapter 10 for more detail) indirectly support this, although both neuroimaging and behavioural investigation would better answer this question. Linck and colleagues (2008) found that both classroom L2 learners and those immersed in an L2 environment, on an intermediate language course, demonstrated stronger inhibitory control compared to monolinguals. Interestingly, the classroom learners showed stronger inhibitory control than the immersed L2 learners. Together, these findings indicate that the bilingual advantage is not specific to early acquisition or an immersed L2 environment, and in young adults it can occur after partaking in a language course.

4.2.1 Bilingualism and cognitive control

Evidence suggests that the bilingual advantage in cognitive control exists at all ages. It has been reported in seven-month old infants growing up in a bilingual environment (Kovács and Mehler, 2009), in toddlers (Poulin-Dubois et al., 2011) and in children (Blom et al., 2014; Morales et al., 2013; Kapa and Colombo, 2013; Engel de Abreu, 2012; Yang et al., 2011; Bialystok, 2011; Martin-Rhee and Bialystok, 2008; Carlson and Metlzoff, 2008) – see Adesope et al. (2010), for a systematic review and a meta-analysis. This effect has also been reported in young adults (Bialystok et al., 2014 – study 2; Luo et al., 2013; Tao et al., 2011; Garbin et al., 2010; Prior and MacWhinney, 2010; Costa et al., 2009, 2008; Bialystok et al., 2004) and in older adults (Bialystok et al., 2014 – study 2; Pelham and Abrams, 2014; Luo et al., 2013; Schroeder and Marian, 2012; Salvatierra and Rosselli, 2010; Bialystok et al., 2008, 2004).

Bilinguals' superior ability to inhibit irrelevant information has been observed on non-linguistic interference tasks that typically involve conflict between an intended correct response and a irrelevant/misleading alternative, such as the Flanker task (Costa et al., 2008; Yang et al., 2011; Tao et al., 2011; Engel de Abreu, 2011; Kapa and Colombo, 2013; Pelham and Abrams, 2014), the Simon task (Schroeder and Marian, 2012; Salvatierra and Rosselli, 2010; Martin-Rhee and Bialystok, 2008; Bialystok et al., 2006, 2004) and the Stroop task (Blumenfeld and Marian, 2014; Hernández et al., 2010; Bialystok and dePape, 2009; Martin-Rhee and Bialystok, 2008). Considerably less research has been conducted on bilingualism and WM capacity, although several studies have reported a bilingual advantage (Blom et al., 2014; Bialystok et al., 2014 – study 2; Luo et al., 2013; Morales et al., 2013). See experimental chapters for a more detailed discussion of most of these studies.

4.2.2 Bilingual language control

Evidence suggests that both L1 and L2 are active when only either of them is in use (Kroll et al., 2014; 2012). Due to this parallel activation, bilinguals need to develop some kind of controlling mechanism in order to minimise intrusions from the language that is not in intended use, otherwise it would be difficult for bilinguals to produce meaningful sentences, and to be understood (Kroll et al., 2014; 2012). This parallel activation has even been shown in bilinguals whose L1 and L2 use different written scripts, for example English and Chinese (Thierry and Wu, 2007). Hence, this does not only happen in bilinguals whose languages are similar. Some reports indicate that having to manage two language systems, and their potential competition can have certain disadvantages. For instance, bilingualism has been associated with an increase in tip-of-the-tongue states (word retrieval failures) (Gollan and Acenas, 2004), and bilinguals have been observed to have a smaller vocabulary in both their languages (Bialystok et al., 2010; Bialystok and Luk, 2012), be slower (Ivanova and Costa, 2008; Costa and Santesteban, 2004) and less accurate (Gollan et al., 2007) to name pictures on picture naming tasks.

The general consensus is that bilingual language control – the experience of focusing on the intended language whilst avoiding intrusions from the unintended language – is the underlying, or related, cognitive process for the bilingual advantage in EF (Green and Abutalebi, 2013; Abutalebi and Green, 2007; Green, 1998). The underlying processes of bilingual language control are thought to include selecting which language to speak and inhibiting words from the language not intended for use. Additionally, those processes are believed to include the operation of monitoring potential conflicts between the language in use and the unintended one; for example, monitoring for interferences from the language not in use, as well as switching between languages (Green and Abutalebi, 2013; Abutalebi and Green, 2007). Initially, the explanation for the bilingual advantage focused on inhibiting interference from the unintended language. Green's Inhibitory Control model (1998) proposed that continuous exercise of managing two languages results in bilinguals becoming experts at inhibiting irrelevant information. That is, extensive practice in selectively attending to relevant information, while ignoring irrelevant information, results in a specific advantage in inhibitory control. However, accumulating evidence indicates wider implications of managing two language systems.

Hilchey and Klein’s (2011) review of non-linguistic interference tasks questioned the hypothesis (Green, 1998) of a specific inhibitory control advantage being responsible for bilinguals’ superior performance. Hilchey and Klein (2011) concluded that a bilingual advantage in inhibitory control was an overall inconsistent finding, rare in children and young adults, and most consistently seen in older adults. However, a robust conclusion from Hilchey and Klein’s review (2011) was that even though bilinguals did not consistently show an inhibitory control advantage (smaller interference effect – incongruent trials minus congruent trials), they typically responded faster than monolinguals on *both* congruent and incongruent trials (e.g., Bialystok et al., 2004; Costa et al., 2008, 2009; Martin-Rhee and Bialystok, 2008). This advantage was observed in all age groups, although sometimes seen in young adults only if task difficulty was high (Bialystok, 2006; Costa et al., 2009). This was in line with a conclusion previously made by Costa et al. (2009), who suggested that bilinguals may be more efficient at monitoring conflict rather than inhibiting it per se. That is, bilinguals may be better than monolinguals at determining when to ignore misleading information. This emerging evidence of the bilingual advantage not being specific to inhibitory control is consistent with Miyake and Friedman’s (2012) unity/diversity framework (see Chapter 3), which indicates that the cognitive control processes share common underlying mechanisms, although some of them can be separated from it (e.g., WM updating).

Both behavioural (e.g., Giezen et al., 2015; Soveri et al., 2011; Blumenfeld and Marian, 2007) and neural evidence suggests that the networks/areas overlap in which bilinguals engage when managing two language systems and cognitive control. This has been referred to as “domain-general cognitive control" mechanisms (e.g., Giezen et al., 2015; Prior and Gollan, 2011; Soveri et al., 2011; Blumenfeld and Marian, 2007). For instance, Prior and Gollan (2011) observed a link between language switching and task-switching, where the more bilinguals reported switching between languages the better they performed on a non-linguistic task-switching task. Similarly, Giezen et al. (2015) showed that the bimodal bilinguals who demonstrated greater inhibitory control on a non-linguistic task (Stroop) spent less time looking at cross-linguistic distractors. The authors suggested this indicates that they were better at resolving language co-activation, or exhibited less co-activation of their languages.

4.2.3 The bilingual advantage beyond cognitive control

There are also reports of superior performance of bilinguals, compared to monolinguals, outside the domain of cognitive control and evidence suggests this may extend to some aspects of memory, such as episodic memory (Bak et al., 2014; Zahodne et al., 2014; Ljungberg et al., 2013; Schroeder and Marian, 2012; Wodniecka et al., 2010). Episodic memory and cognitive control highly correlate (McCabe et al., 2010), therefore it is not unexpected that in the study by Wodniecka et al. (2010), the bilingual advantage was only observed in the aspect of episodic memory that relies on cognitive control. Wodniecka et al. (2010) investigated the bilingual advantage in recollection memory and familiarity memory. It has been suggested that memory retrieval consists of two key components – familiarity and recollection – and these are thought to differ in terms of their reliance on cognitive control. Familiarity is seen as an automatic aspect of memory, but recollection a controlled aspect of memory, as it relies on cognitive control to select particular details of memories (Yonelinas, 2002). Younger and older monolinguals and bilinguals completed both verbal and non-verbal (episodic) memory tasks. Wodniecka et al. (2010) reported a bilingual advantage on the recollection tasks (non-verbal – 1st experiment, verbal – 2nd experiment) in the older adults, but not on the familiarity tasks.

Younger adult groups did not differ but both recalled significantly more than both older groups.

A cross-sectional study by Schroeder and Marian (2012) investigated episodic memory, comparing older monolinguals and bilinguals on a non-verbal picture recall task. The bilinguals recalled significantly more pictures than did the monolinguals, suggesting better episodic memory. They also looked at cognitive control (inhibition), in which bilinguals showed superior performance, and observed a positive association between episodic memory and inhibition, but only among the bilinguals. The authors (Schroeder and Marian, 2012) speculated whether this episodic memory advantage could be explained by superior EF.

In a large sample of 1,067 older adults, where all the bilinguals were immigrants, Zahodne et al. (2014) observed a bilingual advantage in verbal episodic memory, independent of possible confounding factors, such as education, age, and time spent in the L2 country. However, the authors did not state at which age the participants started learning their L2 and how much they used it on a daily basis, which may have influenced the results.

A Swedish 20 year longitudinal study (Ljungberg et al., 2013) investigated episodic memory recall and fluency (verbal letter and categorical) in monolinguals and bilinguals who were 35-70 years old. Most of the bilinguals (64%) did not use their L2 regularly and only did when travelling, while 29% used L2 at work and 7% at home. Nevertheless, a bilingual advantage in episodic memory and letter fluency (but not categorical fluency), was observed, at baseline and across time (four test waves). Also, no age-related differences were found.

These studies suggest that bilinguals have a better episodic memory, but that bilingualism does not attenuate age-related episodic memory decline. Furthermore, the finding (Zahodne et al., 2014; Wodniecka et al., 2010) of a bilingual advantage in verbal episodic memory is noteworthy, as some studies (see section 4.2.2) indicate that bilinguals are disadvantaged when it comes to verbal abilities. However, at least one study has not reported a bilingual advantage in verbal episodic memory, but found bilinguals to recall fewer items compared to monolinguals (Fernandes et al., 2007).

Other areas of cognition have also been implicated in the bilingual advantage, such as creativity (Kharkhurin, 2010). Two recent studies (Hommel et al., 2011; Kharkhurin, 2010) investigated bilingualism and creativity in young adults. Kharkhurin (2010) reported a bilingual advantage in non-verbal creativity (figural responses) but a monolingual advantage in verbal creativity (verbal responses). Hommel et al. (2011) investigated divergent and convergent creativity. Divergent creativity is a “thinking out of the box” type of creativity, where many possible solutions are explored for a given problem/question, whereas convergent creativity is more analogous to critical thinking, where a single (correct) solution to a problem/question is required. Thus, convergent creative thinking should rely more on cognitive control than divergent thinking. Hommel et al. (2011) observed that high proficiency bilinguals outperformed low proficiency bilinguals in convergent thinking but vice versa in divergent thinking. Together with the finding of Wodniecka et al. (2010), this suggests that bilingualism supports cognitive processes which require cognitive control.

The dialogue relating to bilingual advantage and cognition has thus far been mostly positive; indicating that (1) due to the demanding effects of managing two language systems and (2) that both language control and cognitive control mechanisms engage the same domain-general cognitive control mechanisms, and that (3) this advantage has been observed in other cognitive domains that either rely on, or also engage, the domain-general cognitive mechanisms, bilinguals encompass enhanced cognitive control. However, there have been other more neutral or negative reports, which will be talked about in the following section.

4.3 Bilingual advantage in cognitive control - is it too good to be true?

Prior to the start of this project, research on the effects of bilingualism on cognitive control was mostly positive, for bilinguals. However, accumulating evidence shows that this is not as straightforward as it seems. In terms of tasks that tap inhibitory control/monitoring, a bilingual advantage has not been (consistently) observed in the following studies - Gathercole et al., 2014; Kirk et al., 2014; Mor et al., 2014; Paap and Sawi, 2014; Paap and Greenberg, 2013; Namazi and Thordardottir, 2010; Morton and Harper, 2007. In tasks tapping WM there was no language group difference (Ratiu and Azuma, 2014; Bonifacci et al., 2011; Engel de Abreu, 2011; Namazi and Thordardottir, 2010; Martin-Rhee and Bialystok, 2008). These results will be detailed in the introductions to the experimental chapters.

Several studies emerged when data collection for this project was completed, and could therefore not influence the main hypothesis of this thesis. These reported no difference between older monolinguals and bilinguals, in the Simon task (Kirk et al., 2014), inconsistent positive (or negative) effects of bilingualism (Gathercole et al., 2014; Paap and Sawi, 2014; Paap and Greenberg, 2013) and even a bilingual disadvantage in inhibitory control, in young adults, in the Simon task (Paap and Sawi, 2014; Paap and Greenberg, 2013 – data set 3), and in monitoring, in young adults, in the Simon task (Gathercole et al., 2014; Paap and Sawi, 2014).

Gathercole et al. (2014) investigated the bilingual advantage on three tasks (the Simon task, Card sorting task and a metalinguistic task) in participants ranging from children to older adults with all bilinguals being early simultaneous and fully fluent. The bilinguals only spoke English and Welsh, and lived in Wales, whereas the monolinguals lived in England. Across the tasks the authors did not observe an overall bilingual advantage. In the Simon task, language groups responded similarly among children. In terms of accuracy, a bilingual disadvantage was seen in the teenage group and there was no effect of bilingualism in young adults (mean age = 25.5 years). However, in older adults (mean age = 67.6 years) there was a bilingual advantage in accuracy of response. In terms of reaction time, a difference was only seen in young adults, where a bilingual disadvantage was observed in monitoring (global RT), and no differences were observed in inhibitory control. This is clearly problematic for the bilingual advantage literature, especially given the large sample of this study (557 participants completed the Simon task).

Kirk et al. (2014) also investigated cognitive control performance in the Simon task (inhibitory control and monitoring), in older adults (mean age = 70.8 years). The participants were divided into three groups of monolinguals (monolinguals, monodialectal speakers and bidialectal speakers) and two groups of bilinguals (Gaelic and English (non-immigrants) and Asian and English (immigrants)) with the following L1: Bengali, Gujarati, Hindi, Malay, Punjabi and Urdu. As with the monolinguals, the Gaelic and English bilinguals lived in Scotland and the Asian and English bilinguals lived either in Scotland or London. They found no significant group differences in terms of either measure, but a trend towards significance of a bilingual disadvantage for the Asian group was seen in monitoring (slower global reaction times). The authors do not state compared to which group, but according to the descripitives the other four groups show similar reaction times. They also investigated whether test performance could be determined by socioeconomic status (SES), but found no such evidence. The authors stated that the results were also independent of immigrant status and cultural and ethnic background.

Paap and Sawi (2014) compared young monolinguals and bilinguals on four cognitive control tasks (the Simon task, an antisaccade task, an attentional network test, and a colour-shape switching task). The bilinguals had various languages as L1. They observed a bilingual disadvantage in inhibitory control and monitoring in the Simon task, as well as in one measure of the antisaccade task. No other differences were observed. Paap and Sawi (2014) used the same criteria as Paap and Greenberg (2013) when deciding who is a bilingual. They included multilinguals in their "bilingual" cohort: *"our bilinguals are highly fluent in at least two languages* *and 25% are fluent in three or more languages"* (p.5), which may, partly explain their bilingual disadvantage finding. Various languages as L1 may also explain this, although a bilingual advantage has been reported in bilingual cohorts of mixed L1 (e.g., Bialystok et al., 2014; Luo et al., 2013). However, overall, this bilingual disadvantage finding was less consistent than no modulation of language group.

The bilingual inhibitory control disadvantage finding by Paap and Greenberg (2013) and Paap and Sawi (2014) suggests that in some cases speaking two languages, compared to just speaking one, is more taxing for the cognitive system. It could be further argued that speaking three languages, as opposed to two, can be even more of a burden in this respect. As mentioned in Chapter 3 (section 3.3), individuals with chronic tinnitus have been observed to have weaker cognitive control compared to healthy controls (Heeren et al., 2014). As bilinguals, and to an even greater extent trilinguals (see a further discussion on trilingualism in section 4.3), need to inhibit/ignore the language not in use, to follow a conversation; individuals with chronic tinnitus need to inhibit/ignore phantom sounds. The finding of Heeren et al. (2014) indicates that individuals with tinnitus do not develop enhanced cognitive control, even after extensive practice of inhibiting/ignoring phantom sounds for around 11 years on average, suggesting attention overload on the cognitive system. This is converse to what the bilingual advantage hypothesis suggests regarding extensive practice of inhibiting/ignoring the language not in use (see section 4.2.2). Although the way bilingualism and tinnitus affect the cognitive system is not entirely comparable – and as bilingualism, tinnitus is a complex phenomenon (The British Tinnitus Association, 2015) – it can be argued that these phenomena are analogous up to a certain extent, as both groups are thought to experience extensive practice in inhibiting/ignoring irrelevant information. Entertaining this thought, it can be further argued that, perhaps in some cases, bilinguals, too, experience attention overload as a result of having to consistently inhibit/ignore the language not in use. Thus, there is the possibility that managing two languages, compared to only one, presents attention overload, making it more challenging for bilinguals to complete EF tasks. This could explain the bilingual disadvantage findings by Paap and Greenberg (2013) and Paap and Sawi (2014). Similarly, it could be argued that as trilinguals have more languages to inhibit/ignore compared to bilinguals, they may experience an even heavier attention overload, and consequently find it even more challenging to complete EF tasks than bilinguals.

An interesting recent study explored the combined effect of bilingualism and attention deficit hyperactivity disorder (ADHD) (Mor et al., 2014). As an inhibitory control deficit is considered one of the main characteristics associated with this disorder (van Velzen et al., 2014), bilinguals with ADHD should intuitively demonstrate an advantage on tasks tapping inhibitory control, as the inhibitory control deficit should be reduced or neutralised in bilinguals. Mor et al. (2014) divided eighty young adults into groups of monolinguals and bilinguals; one half of each group had a diagnosis of ADHD and the other half did not. The tasks used to tap inhibition were the Numeric Stroop task and the Simon arrow task. Unsurprisingly, participants with ADHD responded less accurately than controls in incongruent trials, on both tasks. Interestingly, and against their hypothesis, Mor et al. (2014) observed a more pronounced negative impact of ADHD on bilinguals compared to monolinguals. Reaction time analyses showed that on both tasks, monolinguals, with and without ADHD, showed similar performance, but for bilinguals the interference effect was larger in those with ADHD than those without. Interestingly, no language group differences were seen in monitoring (global RT) or other aspects of cognitive control, such as shifting. Although replication is needed, it would be interesting to investigate this in other disorders that have been associated with inhibition deficits, such as depression (Snyder, 2013), obsessive-compulsive disorder (van Velzen et al., 2014) and schizophrenia (Barch and Ceaser, 2012). This finding indicates that bilingualism does not improve EF impairments, such as deficits in inhibition. The authors suggested that adult bilinguals who suffer from ADHD may suffer more due to managing two languages. However, this study did not look at WM, which is thought to share a common underlying mechanism with inhibition (e.g., Miyake and Friedman, 2012) and would be both interesting and informative for future study.

Nevertheless, this, along with the non-bilingual advantage findings stated above, indicates that not all bilinguals enjoy cognitive control benefit, or that there are other, unexplained, confounding factors (apart from proficiency, L2 AoA and language use) that influence the findings on bilingualism and cognition. For example, physical and cognitive activity, or, as this thesis speculates, how strictly researchers classify bilinguals, i.e., whether their bilingual cohorts are bilinguals only, or also include participants who speak more than two languages regularly.

4.3 Trilingualism

Following on from the hypothesis that actively speaking two languages makes bilinguals experts in cognitive control, it can be argued that actively speaking more languages, such as three, means higher expertise; that is, more cognitive control. As there are brain related differences between monolinguals and bilinguals (in language processing areas), and the latter group is often found to outperform the former on measures mediated by overlapping areas, it seems logical to assume that, similarly, brain related areas are different between bilinguals and multilinguals. Evidence for this (at least in terms of structure) comes from a recent study by Grogan et al. (2012), who found higher grey matter density in young multilinguals, compared to their bilingual counterparts, in the same region (inferior parietal lobule – important for vocabulary) where Mechelli et al. (2004) found higher grey matter density in bilinguals compared to monolinguals. Grogan et al (2012) suggested that this reflects that multilinguals have a larger overall vocabulary than bilinguals due to speaking more languages. L2 AoA and L2 proficiency (or English for multilinguals) did not significantly differ between groups. Not comparable with these studies is the fact that Grogan et al. (2012) found significant effects in the right inferior parietal lobule and a trend in the left, but Mechelli et al. (2004) observed the opposite pattern. Importantly, and unlike Mechelli et al. (2014) Grogan et al. did not find any association between L2 AoA and grey matter density.

Given this finding, it is not surprising that Kavé et al. (2008) observed better cognitive performance on the Mini Mental State Examination (MMSE), and the Short Orientation Memory Concentration Test (OMCT), with increasing number of languages in older adults. That is, trilinguals performed better than bilinguals, and multilinguals better than both previously mentioned groups. General fluid intelligence has also been observed to be higher in older multilinguals, compared to bilinguals, after controlling for childhood intelligence (Bak et al., 2014). Investigations into enhanced cognitive control have also been conducted in five to eight year old children (monolinguals, second language learners, bilinguals and trilinguals) (Poarch and van Hell, 2012, experiment 1); see Chapter 5, section 5.3.1, for a more detailed description of the study. On the inhibitory control measure (Simon effect – see Chapter 5, section 5.1.2) the data indicated stronger inhibitory control with increasing number of languages, but the only significant differences detected were between trilinguals and monolinguals, and a trend was seen between bilinguals and monolinguals ($p = .062$). Thus, although this suggests that trilinguals do have more advantage over monolinguals, compared to bilinguals, it does not provide concrete evidence for the notion that he more languages need to be manages the stronger inhibitory control, as the second language learners, bilinguals and trilinguals did not significantly differ. Additionally, according to new evidence, which could not influence the main hypothesis of this thesis, Paap et al. (2014) reported that young trilinguals were outperformed by monolinguals in inhibitory control, although significant difference was not detected between bilinguals and trilinguals (Paap et al., 2014). See Chapter 5, sub-section 5.1.3.2, for more details of this paper.

Furthermore, as can be seen in Chapter 2, there is evidence to suggest speaking three or more languages has a more protective effect against developing dementia (or delaying it). For instance, Chertkow et al. (2010) found no protective effect of bilingualism, apart from in the immigrant cohort, but found a significant protective effect of speaking three or more languages. Also, a lower risk of an MCI diagnosis has been observed in individuals who spoke more than two languages, compared to bilinguals (Perquin et al., 2013). However, as was stated in Chapter 2, this multilingualism protective effect is not always found (Alladi et al., 2013).

4.4 Chapter summary

This chapter has given a review of the cognitive consequences of bilingualism, both in relation to cognitive control and other cognitive domains. Importantly, the chapter shows that the evidence is inconsistent. Consequently, this chapter has suggested that possible confounding factors other than proficiency, L2 AoA and language use needs investigation. These other factors include physical activity, cognitive activity and the make-up of the “bilingual” cohorts. Lastly, besides the importance of examining potential confounding effects in trilinguals’, there is also a gap in the literature regarding whether more languages result in stronger cognitive control in young to older adults. Hence, trilingualism is an under-researched area that needs investigation.

Chapter 5: The effects of trilingualism and ageing on inhibitory control and monitoring

5.1 Introduction

As the previous chapter demonstrated, research on bilingualism and cognition has revealed positive effects of bilingualism on EF. This has been predominantly evident on non-linguistic EF tasks which tap into cognitive control, although there are other studies that have not observed this positive effect. As previously mentioned, cognitive control is thought to include the ability to inhibit irrelevant information (inhibitory control) and update information in WM (e.g. Miyake and Friedman, 2012; Friedman et al., 2008; Miyake et al., 2000), and the bilingual advantage particularly been associated with inhibitory control. However, as seen in Chapter 4, the bilingual advantage may have wider implications than just for inhibitory control. For instance, Hilchey and Klein (2011) proposed that bilinguals may have a more general processing advantage (global advantage), and therefore better at monitoring attention.

To date there has been limited research on the effect of trilingualism on inhibitory control and monitoring, and recent work has mainly focused on children. Also, previous research, comparing monolinguals and bilinguals, used predetermined age-groups to examine age effects, producing results that are not entirely in agreement. Therefore, perhaps a different method of looking at the relationship between cognitive control and age is needed in this context. Two recent studies (Goral et al., 2013; Soveri et al., 2011) looked at age on a continuum, but in middle-aged and older bilinguals only. Furthermore, they did not look at monitoring performance, in which, according to previous research (Hilchey and Klein, 2011), bilinguals have more consistently shown an advantage.

This chapter investigates whether the bilingual advantage in inhibitory control and monitoring can be extended to trilinguals, and by looking at age on a continuum it also investigates whether there are any age-related differences between young adult to older adult monolinguals, bilinguals and trilinguals.

5.1.1 The Simon task

The commonly used Simon task (Simon and Small, 1969) is a measure of interference suppression (inhibition of task-irrelevant information) and is based on stimulus-response compatibility (SRC), which refers to the idea that responses are faster and more accurate when stimulus and response correspond than when they do not (Hommel, 2011). On a typical Simon task participants respond to different coloured squares (red and blue for example) on either the left hand side or the right hand side of the screen, by pressing either the corresponding left or a right button. The task usually includes two types of trials; a congruent trial and an incongruent trial. On congruent trials the stimulus (square) and response correspond i.e., target presented on the left hand side of the screen and the response is the left button, but on incongruent trials they do not i.e., the target is presented on the left hand side of the screen but the colour indicates that the right hand button should be pressed.

There are two important markers when investigating a bilingual advantage on an interference task such as the Simon task; these are (i) a smaller magnitude of the Simon (interference) effect (also referred to as conflict effect), which is the difference in response time and accuracy between incongruent and congruent trials and (ii) a faster global reaction time, which is overall performance on both congruent and incongruent trials (Costa et al., 2009; Hilchey and Klein, 2011).

5.1.3 Recent work exploring the bilingual advantage in trilinguals

The studies reported in this section were published after the start of this project, except the Porach and van Hell (2012) study was published around the same time the data collection for the present chapter took place.

5.1.3.1 Children

Poarch and van Hell (2012) examined inhibitory control and monitoring processes, using the Simon task. They tested children living in Germany, aged between five and eight. The sample consisted of the following: (i) monolinguals, (ii) second language learners (native German speakers with English as a second language), (iii) bilinguals (German-English) and (iv) trilinguals (German/English and various other languages). They observed that in terms of inhibitory control, both trilinguals and bilinguals significantly outperformed monolinguals, although bilinguals marginally ($p = .062$). The authors pointed out that second language learners also showed a smaller Simon effect compared to monolinguals, but this did not reach statistical significance. However, there were no significant differences between the groups in terms of monitoring which was classified as global (overall) reaction time.

These results indicate that both bilingual and trilingual children show enhanced inhibitory control compared to monolinguals. This is in line with some previous work (Martin-Rhee and Bialystok, 2008; Bialystok et al., 2004). However, the results also indicate that controlling more languages is not equivalent to strengthened inhibitory control as the second language learners, bilinguals and trilinguals did not significantly differ. Furthermore, neither bilingual nor trilingual children manifested enhanced monitoring compared to monolinguals, and, as in the case of inhibitory control, monitoring did not improve with more than two languages. The lack of group differences in terms of monitoring, particularly between monolinguals and bilinguals, is not in line with previous findings (Bialystok et al., 2004). This is surprising as Hilchey and Klein's (2011) review found that the bilingual advantage in monitoring is more consistent than in inhibitory control. Why these two mechanisms (inhibitory control and monitoring) sometimes seem to be affected differently by bilingualism needs further exploring in monolinguals, bilinguals and trilinguals, particularly in older age groups than children.

5.1.3.2 Young adults

The effect of trilingualism on EF was recently examined in young adults by Paap et al. (2014), where Paap and colleagues pooled data from Paap and Greenberg (2013) and Paap and Sawi (2014), whereby Paap and Greenberg (2013) reported a bilingual disadvantage in inhibitory control only in the Simon task, and Paap and Sawi (2014) in both inhibitory control and in monitoring, on the same task. After pooling data from both papers, Paap et al. (2014) reported no evidence of a bilingual advantage on twelve markers of EF, obtained from the Simon task, Flanker task and the antisaccade task. They did, however, report a bilingual and trilingual disadvantage, compared to monolinguals, in inhibitory control (Simon effect), but the groups performed similarly in terms of monitoring (global RT). Also, the bilinguals and trilinguals did not differ on either measure, and all groups showed similar monitoring performance, matching the findings of Poarch and van Hell (2012 – experiment 1). Nonetheless, this pattern (disadvantage) is the opposite to that of Poarch and van Hell's (2012, experiment 1), who observed a trilingual inhibitory control advantage in children (compared to monolingual counterparts). These two findings, a trilingual advantage in children (in inhibitory control) and a trilingual disadvantage in young adults (in inhibitory control) are perplexing, especially since monitoring was not seen to differ between trilinguals and monolinguals. Furthermore, both studies suggest that there is no added benefit of managing three languages, as opposed to two. The present chapter will, therefore be highly informative, as replication and further research is needed in young adults, and this also needs to be looked at in older adults.

5.1.3.3 Older adults

Although no study has investigated the effect of trilingualism in the Simon task (as far as I am aware), some evidence suggests that older trilinguals/ multilinguals may enjoy increased cognitive benefits compared to bilinguals. A longitudinal study by Bak et al. (2014) observed, after controlling for childhood intelligence (around 11 years of age), that in older adults (73 years of age) multilinguals (individuals who spoke three or more languages) showed increased general fluid intelligence compared to bilinguals and monolinguals. According to Friedman et al. (2006), general fluid intelligence is not thought to be associated with inhibition, but with WM, which will be investigated in Chapter 6. Nevertheless, this, and the findings by Poarch and van Hell (2012) indicate that for adults, there may be an added benefit in cognitive control, with added number of languages. This is particularly convincing, taking into consideration the finding of structural differences between bilinguals and multilinguals in the right posterior supramarginal gyrus (a part of the inferior parietal lobule), where multilinguals were observed to have higher grey matter density than bilinguals (Grogan et al., 2012). This is the same area in which bilinguals were reported to have higher grey matter density compared to monolinguals in the study by Mechelli et al. (2004). Although, taking the new evidence from Paap et al. (2014) into consideration, this may be more complex than that.

5.1.4 Previous investigations of ageing effects in bilinguals

It is generally assumed that EF efficiency decreases with normal ageing (Grady, 2012; Reuter-Lorenz and Park, 2010; Takio et al., 2009; Kray et al., 2004; Zelazo et al., 2004). Compared to younger adults, older adults have been found to be less able to ignore/reject irrelevant information (Tun et al., 2002), to show decreased inhibitory control and to have a slower response time to visual stimuli (Proctor et al., 2005; Van der Lubbe and Verleger, 2002).

Bialystok et al. (2004) investigated age-related effects in young adult (mean = 42.8 years, age range = 30-54 years) and older adult (mean = 71.1 years, age range = 60-88 years) monolinguals and bilinguals. They found that bilinguals outperformed monolinguals, both in terms of monitoring and inhibitory control (in both a simple and complex condition). These effects were seen in both young adults and older adults, and the difference between monolinguals and bilinguals increased with age.

Salvatierra and Rosselli (2010) partially replicated the findings of Bialystok et al. (2004). They investigated young (mean = 26 years) and older (mean = 64 years) adults, and although they found a bilingual advantage in both monitoring and inhibitory control, this advantage was only apparent in older adults, and only in the simple condition. Schroeder and Marian (2012) also investigated the bilingual advantage in older adults (mean age = 81 years, age range = 73-88), divided into monolinguals and bilinguals. Inconsistent with some previous findings, they found that the two language groups did not differ in monitoring, but did so in terms of inhibitory control, with bilinguals outperforming monolinguals. Although these studies show some inconsistencies, they indicate that at least for older adults a bilingual advantage does exist. However, studies published after data collection was completed for this thesis, show more inconsistencies, and even a bilingual disadvantage. See Table 2 below.

Table 2. Simon task performance and inconsistent findings among bilinguals

Studies	Age group	Monitoring	Inhibitory control
Paap and Sawi (2014)	Young adults	Bilingual disadvantage	Bilingual disadvantage
Paap and Greenberg (2013)	Young adults	No difference	Bilingual disadvantage
Gathercole et al. (2014)	Young adults	Bilingual disadvantage	No difference
	Older adults	No difference	No difference
Salvatierra and Rosselli (2010)	Young adults	No difference	No difference
	Older adults	Bilingual advantage	Bilingual advantage
Bialystok et al. (2004)	Young adults	Bilingual advantage	Bilingual advantage
	Older adults	Bilingual advantage	Bilingual advantage
Kirk et al. (2014)	Older adults	No difference	No difference
Schroeder and Marian (2012)	Older adults	No difference	Bilingual advantage

Looking at age on a continuum, Goral et al. (2013) investigated age-related changes in inhibition in Spanish-English bilinguals, aged 50 to 84 years old (a monolingual sample was not included), but did not investigate monitoring. They found that age was a significant predictor of the magnitude of the Simon effect, which increased with age. That is, inhibitory control significantly decreased with age in their bilingual sample. This was however, not the same pattern as seen in Soveri et al. (2011), who also looked at age-related changes on a continuum in bilinguals, and found that age did not predict the Simon effect.

The discrepancies in results between the two studies (Goral et al., 2013 and Soveri et al., 2011) may be caused by differences in characteristics between the bilinguals in each study. For example, bilinguals in Goral et al. were older (50-84 years, mean age = 63.44 years) than in the study by Soveri et al. (2011) bilinguals (30-75 years, mean age = 52.8 years) and had spent fewer years in education (difference = 2.45 years). Bilinguals in Soveri et al. (2011) were all early bilinguals (mean age = 4 years) and equally proficient in both their languages, whereas in the case of Goral et al. they ranged from early to late (mean age = 13.54 years) and were more proficient in their L2 than L1. Further to this, there were more trials in Goral et al. (192) than in Soveri et al. (100), although the Simon effect was similar (~45 ms).

In summary, previous research has shown inconsistent findings using the Simon task, both in terms of inhibitory control and monitoring. However, looking at age, these two effects seem to be most consistently seen in older adults, suggesting that positive effects of managing two languages only become apparent in older adults, who have more years of bilingual experience (Salvatierra and Rosselli, 2010).

It has been suggested that the conflicting evidence on the bilingual advantage in inhibitory control and monitoring may be due to other confounding factors (Hilchey and Klein, 2011), such as socioeconomic status (SES), which may contribute towards these mixed results.

5.1.5 The presence of trilinguals in a bilingual group

In the light of inconsistent findings in the bilingual advantage literature, all possible confounding factors need exploring, one of which is the presence of trilinguals or multilinguals in the bilingual group. One way to investigate whether speaking three languages affects task performance is to compare bilinguals and trilinguals' performance, making sure group allocation is stricter, whereby the bilingual group includes *true* bilinguals and the trilingual group includes *true* trilinguals only. If a trilingual advantage, but not bilingual advantage, is found it could indicate that previous studies did not adequately control for bilingualism and reported a bilingual advantage when it was really a trilingual advantage. Similarly, if a trilingual disadvantage is found, it could mean that some previous studies, which found no difference between monolinguals and bilinguals, did actually show a bilingual advantage but the presence of trilinguals (or multilinguals) in the group confounded the results. It is not being argued here that this is the case with all studies, but the fact that some researchers report that the "bilingual" cohort included multilinguals suggests that this may be a wider problem. Recent examples in the EF/bilingualism literature are Paap and Sawi (2014), Paap and Greenberg (2013) and Coderre and van Heuven (2014). For example, Coderre and van Heuven (2014), reported that 16 out of 25 bilinguals knew other languages apart from their L1 and L2, and that six bilinguals also spoke a third language. Twenty five percent of Paap and Sawi's (2014) "bilingual" cohort were fluent in three or more languages. Paap and Greenberg (2013) also included multilinguals in their "bilingual" cohort, although they did not state how many. Noteworthy is that both Paap and Greenberg (2013) and Paap and Sawi (2014) observed a bilingual disadvantage in the Simon task (see Table 2), which could possibly be explained by the fact that their "bilingual" cohorts were not pure. What makes this speculation particularly convincing is that when Paap and colleagues pooled the data from Paap and Greenberg (2013) and Paap and Sawi (2014) they observed a trilingual disadvantage compared to monolinguals, as well as the bilingual disadvantage they observed in the initial studies.

5.2 The present study: research aims

The present chapter examines the bilingual advantage in monolinguals, bilinguals and the understudied sample of trilinguals. Possible effects of age will also be explored, by looking at age on a continuum, from young adults to older adults. Factors under investigation are both inhibitory control and monitoring, which will be tapped into using the Simon task. Investigating trilinguals in this context will also shed some light on whether including participants who speak more than two languages in a "bilingual" group has a confounding effect on their result.

Inhibitory control: Based on the assumption that trilinguals have undergone the most extensive training in language control, bilinguals somewhat less, and monolinguals none, it is predicted that trilinguals will show the strongest inhibitory control and monolinguals the weakest. Poarch and van Hell (2012), however, did not note a statistical difference between bilingual and trilingual children (mean age = 6.9 years) and Paap et al. (2014) observed a trilingual disadvantage in terms of inhibitory control. Nevertheless, it is predicted that this may be seen in older participants, since previous findings have shown that the difference in inhibitory control performance between monolinguals and bilinguals increases with age (Bialystok et al., 2004). Although the recent result of Paap et al. (2014) provides indications to the contrary.

Monitoring: Based on the evidence that bilinguals have been quite consistently found to outperform monolinguals in global reaction time (monitoring) in the Simon task – which is presumed to be associated with enhanced monitoring capacity in bilinguals – it is hypothesised that monolinguals will show the weakest and trilinguals the strongest monitoring performance.

Age: Based on the evidence that, compared to monolinguals, bilinguals have shown an advantage in both inhibitory control and monitoring, which remains constant with age (Bialystok et al., 2004) and that this advantage was only seen in older adults in Salvatierra and Rosselli's (2010) study, it is expected that the association between age, and that of both inhibitory control and monitoring, becomes weaker with growing number of languages spoken. That is, the association with age is the strongest among monolinguals and weakest among trilinguals.

5.3 Methods

5.3.1 Participants

One hundred and thirty two (95 females and 37 males) monolinguals (N = 40), bilinguals (N = 58) and trilinguals (N = 34) participated in this experiment. Overall, participants' age ranged from 18 to 70 years (M = 29.86 years, SD = ±13.80 years).

The inclusion criteria for participation were no history of uncorrectable visual impairments or dyslexia. For the over 65 years, participation required no existing diagnosis of cognitive impairments or difficulties such as dementia or Alzheimer's. Bilinguals were included if they spoke two languages on a daily basis and trilinguals if they spoke three languages on a daily basis. Bilinguals and trilinguals with L2 AoA from birth and onwards were welcome. Ethics approval was obtained from the Humanities, Social, and Health Science Research Ethics Committee at the University of Bradford. All participants provided informed consent.

Monolinguals

All monolinguals had English as their first language and were not functionally fluent (able to hold a conversation) in any other language.

Bilinguals

Most bilinguals had English as their second language (except Urdu, N = 2, Icelandic, N = 1, Spanish, N = 1) and various languages as their first language. Four had English as their first language. The non-English languages were Arabic (N = 4), Estonian (N = 3), Greek (N = 8), Gujarati (N = 2), Icelandic (N = 3), Urdu (N = 7), Romanian (N = 2), Polish (N = 4), Punjabi (N = 6), Yoruba (N = 2) Bemba, Bulgarian, French, German, Hindi, Hungarian, Korean, Maltese, Pashto, Serbian, Somali and Turkish and Twi (N = 1 each).

Trilinguals

Trilinguals had various languages as a first language [Arabic (N = 2), English (N = 3), German (N = 3), Gujarati (N = 2), Kurdish (N = 2), Latvian (N = 2), Punjabi (N = 9), Urdu (N = 2), Bulgarian, Hinko, Icelandic, Indonesian, Kirundi, Polish, Russian, Spanish and Yoruba (N = 1 each)]; as a second language [English (N = 12), French (N = 3), Swedish (N = 2), Urdu (N = 5), Arabic, Betawi, Chinese, Danish, Greek, Hindi, Latvian, Norwegian, Potwari, Punjabi, Russian and Spanish (N = 1 each)]; and as a third language [English (N = 17), French (N = 2), Russian (N = 2), Punjabi (N = 3), Urdu (N = 6), Arabic, Chinese, Hindi and Spanish (N = 1 each)].

5.3.2 Materials

5.3.2.1 Lifestyle questionnaire

The lifestyle questionnaire (see Appendix 1) included demographic information, physical and mental activity and language use. It contained questions about age, number of years in formal education, country of origin and physical and cognitive activity. Participants were also asked which languages they spoke and age of L2 AoA. Furthermore, they provided self-rated proficiency in L1 and L2 on a 5-point scale (1 = very poor to 5 = very good) and language use per day in percentages (L1, L2 and L3 (trilinguals) totalled 100%). Self-ratings of language proficiency have been found to strongly correlate with objective and standardised measures of language proficiency (Luk and Bialystok, 2013, Marian et al., 2007).

5.3.2.2 Simon task

In this task, participants viewed red or blue squares in the left or right visual field on a computer screen. They were instructed to fixate on a central cross (“+”) which was present at the beginning of each trial (duration 1000 milliseconds) after which it vanished, followed by a 250 ms blank interval. After this, a blue or a red square appeared for 250 milliseconds. Participants were instructed to press the left key (the ‘X’ key) each time a blue square appeared and the right key (the ‘.’ Key) when a red square appeared. On congruent trials the blue square was presented on the left and red on the right, and on incongruent trials, the blue square on the right and red on the left. See Figure 3 for a diagram of both trials. There were 40 congruent trials and 40 incongruent trials (total 80 trials), which were presented randomly. There were eight practice trials. Please see section 5.1.1 for more details on the Simon task.

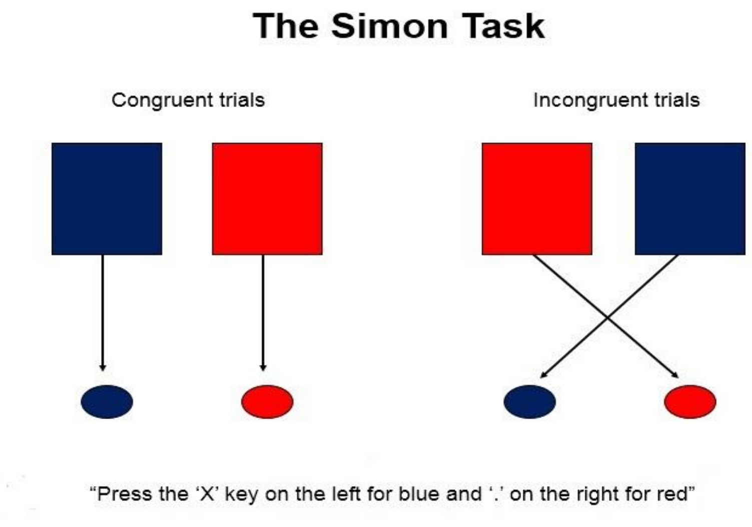

Figure 3. A diagram depicting the two types of trials in the Simon task; congruent and incongruent.

5.3.3 Design

The study utilised a quasi-experimental design, where monolinguals, bilinguals and trilinguals were compared on the following measures:

(i) inhibitory control: The indicator for inhibitory control was calculated as the difference in reaction times (in milliseconds) between incongruent and congruent trials. This will be referred to as the Simon effect from now on.

(ii) monitoring: The marker for monitoring was global reaction time, which is the reaction time (in milliseconds) for congruent trials and the reaction time for incongruent trials analysed independently.

5.3.4 Procedure

The younger participants (64 years and younger) were all recruited from the University of Bradford. They were invited to participate via email letters sent out by administrative secretaries of school divisions at the University of Bradford. The study was also advertised in the Student Telegram and the Staff Briefing. In addition, a recruitment E-mail was sent to the Bradford Cognition and Brain Group mailing list. The older participants (over 65 years) were recruited from University of Bradford Psychology Department Participant Pool. The participant pool is a database of people who have volunteered their details to take part in psychology research at the Division of Psychology. They were recruited via local community centres and groups. The sessions took place in the Psychology Laboratories in the Division of Psychology at the University of Bradford. On arrival, participants were allocated individual cubicle rooms where consent was obtained. The testing session then commenced.

5.4 Results

The present study investigated the bilingual advantage in inhibitory control and monitoring, in monolinguals, bilinguals and trilinguals, and any age-related effects.

5.4.1 Characteristics and background measures

Age: age, which ranged from 18 to 79 years, did not differ between the language groups. *Gender:* there were no gender differences in terms of performance. *Education:* both bilinguals and trilinguals had spent significantly more years in education than monolinguals (both $p < .05$) (monolinguals: mean = 15.42 years, bilinguals: mean = 17.00 years, trilinguals: mean = 17.27 years). *L2 AoA:* bilinguals acquired L2 significantly later ($p < .02$) than trilinguals (mean difference = 5.02 years). *Balanced language skills*[1]*:* participants were asked to provide self-rated overall proficiency on a scale of 1 to 5 in their L1, L2 and L3 (bilinguals: L1 mean = 4.35 and L2 mean = 4.22; trilinguals: L1 = 4.45, L2 = 4.53, L3 = 4.01) with no significant difference between bilinguals L1 and L2 proficiency, and trilinguals L1 and L2. *Daily language use:* bilinguals used L2 (mean = 63.11, SD = ±24.02) significantly more ($p < .001$) than L1 (mean = 35.84, SD = ±23.40). Trilinguals used their L3 (41.79, SD = ±36.37) significantly more ($p <.05$) than L1 (mean = 23.03, SD = ±21.64), but L2 use (35.18, SD = ±33.45) did not differ from the other two languages. As, improved EF has been associated with higher SES (Hilchey and Klein, 2011; Morton and Harper, 2007), years of education was taken as an index of SES (Bialystok et al., 2008; Emmorey et al., 2008).

[1] Note that L1 and L2 proficiency was not found to predict non-verbal performance on executive tests (Simon task and Trail making test) in Goral et al. (2013), and no difference between high versus low L2 proficiency in task-switching (Xie, 2014).

5.4.2 Analysis

Mean response latencies (RTs) and mean accuracy scores were calculated for each participant, and only scores for correct responses were used in the analysis. Outliers of more than two SDs from the mean were excluded from the analysis (less than 5%). An alpha level of .05 was used in all statistical analysis.

In order to confirm that a Simon effect was obtained in the present sample, congruent and incongruent measures were submitted to a paired-samples t-test. Participants responded significantly faster on congruent trials than incongruent trials ($t\ (131) = -16.08$, $p < .001$), which confirmed a significant Simon effect was obtained ($M = 47.36$ ms).

The data were submitted to a multivariate general linear model (GLM), with Simon effect accuracy (%) and Simon global accuracy (%) as dependent variables with language group (monolinguals, bilinguals, trilinguals) as a fixed factor and age and years of education as covariates. To investigate any age effects, an interaction term of language group x age was also included in the model. This was repeated for the RT measures.

5.4.3 Simon accuracy

Accuracy in the Simon task was similar across groups [monolinguals (mean = 92.74 %), bilinguals (mean = 90.80 %), trilinguals (mean = 92.03 %)] and the multivariate GLM analysis did not yield significant main effects for language group or age, or a significant language group x age interaction on the Simon accuracy measure.

5.4.4 Simon reaction time

The multivariate GLM analysis revealed a main effect of language group on the global RT (monolinguals: $M = 326.43$, $SD = \pm 13.25$; bilinguals: $M =$

309.03, SD = ±11.00; trilinguals: M = 308.32, SD = ±14.37), F (1,125) = 3.73, $p < .05$, although pairwise comparisons failed to find significance between each individual language group. There was a trend to a main effect of language group on the Simon effect (F (1,125) = 2.42, p = .093). The multivariate GLM analysis also revealed a strong main effect of age on both the Simon effect (F (1,125) = 5.54, p = .02) and global RT (F (1,125) = 15.64, $p < .001$), where participants showed an increased magnitude of the Simon effect and were slower with age. This is an unsurprising result as a number of studies have shown that RTs on the Simon effect increase with age (Van der Lubbe and Verleger, 2002; Bialystok et al., 2004; Salvatierra and Rosselli, 2010).

5.4.5 Language group x age interaction

As stated previously, language group x age interaction was submitted to the model and an interesting pattern emerged. In monolinguals the magnitude of the Simon effect (Figure 4a) seemed to be differently affected by age, compared to bilinguals and trilinguals. The multivariate GLM analysis revealed this interaction (language x age) to be significant for the Simon effect with F (2,125) = 3.83, $p < .03$. To analyse this further, the data were submitted to a regression analysis, with Simon effect (RT) as a dependent variable and age as a covariate. This was done separately for each language group. The analysis revealed that the Simon effect only showed a linear relationship with age for the trilingual group with $\beta = 11.77$ 1.25, SE = 14.02, (F (1, 32) = 7.18, $p < .02$), y-axis intercept = 1.25 (SE = .47), with regression correlation coefficient r = .43, $p < .01$. This indicates that the ability to inhibit irrelevant information remained stable with age in monolinguals and bilinguals, but decreased in trilinguals.

Regarding global RT, Figure 4b depicts the language group x age interaction for this variable. The multivariate GLM analysis revealed this interaction (language x age) to be significant with (F (2,125) = 4.47, $p < .02$). As with the Simon effect, global RT was submitted to a regression analysis, with global RT as a dependent variable and age as a covariate. The analysis revealed that global RT showed a linear relationship with age in monolinguals and trilinguals, but not bilinguals: Monolinguals; β = 200.07 (SE = 26.95), (F (1, 38) = 27.10, p < .001), y axis intercept = 3.73, (SE = .72), with regression correlation coefficient r = .65, p < .001, Trilinguals; β = 239.55 (SE = 36.07), (F (1,32) = 4.22, p < .05), y axis intercept = 2.46, (SE = 1.20), with regression correlation coefficient r = .34, p < .03. This suggests that bilinguals' monitoring remained stable with age whereas trilinguals, and to a greater extent monolinguals, found it increasingly harder to monitor their attention with age.

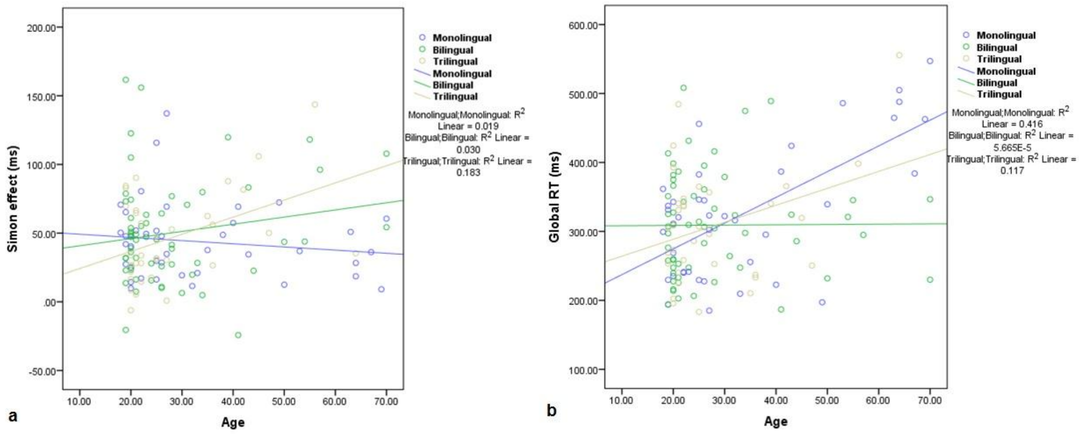

Figure 4 shows scatter plots of the interaction between language group x age for (a) the Simon effect and (b) the global RT

To investigate a trilingual 'advantage' in the younger participants and a trilingual 'disadvantage' in the older participants for the Simon effect, monolinguals and bilinguals were grouped together and compared to the trilingual group. See Figure 5a. The crossover point is 28.63 years. An independent samples t-test was carried out on the two groups and with a trend to significance found in the younger group (under 28.63 years), t (88) = 1.47, p = 0.15. A significant trilingual disadvantage was seen in the older age group (participants over 28.63 years), t (40) = -2.03, p < 0.05.

Regarding global RT, a similar pattern of results is seen, see Figure 5b, but in this case monolinguals and trilinguals were grouped together. The crossover point this time is 28.85 years. Independent samples t-tests showed no significance for either the young or the old group.

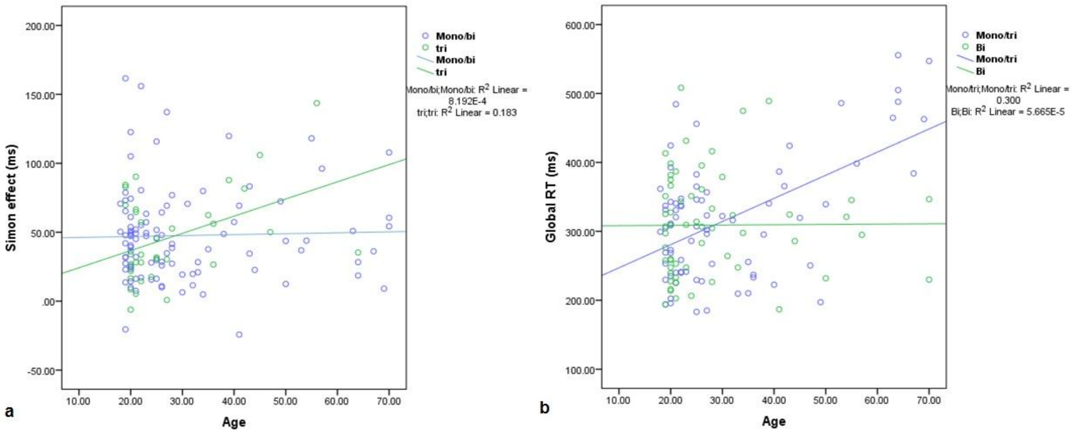

Figure 5 shows scatter plots of the interaction between (a) monolinguals/bilinguals and trilinguals x age for the Simon effect and (b) monolinguals/trilinguals and bilinguals x age for the global RT

5.5 Discussion

The present chapter investigated the proposed bilingual advantage as measured by the Simon task, either in terms of the Simon effect or global reaction time (RT) performance, in monolinguals, bilinguals and trilinguals, and how these processes are affected by age. This was investigated by looking at overall change across age rather than comparing different age groups, a method adopted by previous studies, such as Bialystok et al. (2004) and Salvatierra and Rosselli (2010).

5.5.1 Main findings

All language groups responded similarly to the stimuli with regard to accuracy. Without looking at age, the Simon effect (RT) was similar across groups.

Surprisingly, trilinguals' performance was clearly most affected by age, where a significant age-related decline was observed in both the Simon effect and global RT. In fact, for the Simon Effect a significant trilingual

disadvantage was found in the older group of participants (after the age of 28.63). Monolinguals showed a significant age-related decline in global RT but not in the Simon effect, and bilinguals in neither Simon effect nor global RT.

5.5.2 Main effect of language group

Without looking at age, the results indicate that all three language groups responded similarly, both in terms of response accuracy and reaction time. It is noteworthy that the task used in the present chapter was high in monitoring, in that 50% of trials were congruent and 50% were incongruent. It has been previously observed that a bilingual advantage in monitoring is more likely to be seen in conditions involving high-monitoring demands than low-monitoring (e.g. 92% congruent trials and 8% incongruent trials) on a Flanker task (Costa et al., 2009), which, as the Simon task, involves ignoring distracting information. In terms of monitoring, these results are in agreement with Poarch and van Hell (2012) and previous studies that did not find a bilingual advantage in monitoring (Gathercole et al., 2014 – older adults only; Kirk et al., 2014 – older adults; Paap and Greenberg, 2013 – young adults; Salvatierra and Rosselli, 2010 – young adults only). This is also in line with Paap et al. (2014) who did not find any differences in monitoring between monolingual, bilingual and trilingual young adults. In terms of inhibitory control, these findings are inconsistent with those studies that found a bilingual advantage (Schroeder and Marian, 2012 – older adults; Salvatierra and Rosselli, 2010 – older adults only; Bialystok et al., 2004 – both young and older adults). However, consistent with Paap and Greenberg (2013), and Paap and Sawi (2014), who found a bilingual disadvantage in young adults, and Paap et al. (2014), who found a trilingual disadvantage after pooling data from those studies. It should be noted that the age in the present sample ranged from 18 to 70, and around 70% were under the age of 30. This may explain the non-significant result as a bilingual advantage has not been consistently found in young adults (see Hilchey and Klein, 2011, for a review).

5.5.3 Language group x age interaction

The finding that age did not predict the scores on the Simon effect and global RT for bilinguals is in line with previous findings that compared young adults to older adults (Salvatierra and Rosselli, 2010; Bialystok et al., 2004), and of Soveri et al. (2011) who looked at age-related changes in 30 to 75 year old bilinguals on a continuum and found that age did not predict the magnitude of the Simon effect, although not in agreement with Goral et al. (2013), who observed an age-related decline in the Simon effect in 50 to 84 year old bilinguals.

The trilingual disadvantage in inhibitory control in older than 29 year olds contrasts results by Kavé and colleagues (2008), who compared performance of elderly bilinguals, trilinguals and multilinguals on two cognitive screening tests [Mini Mental State Examination (MMSE) and Short Orientation Memory Concentration Test (OMCT)]. MMSE assesses time orientation and orientation to place, memory, concentration, language and copying and OMCT assesses time orientation, memory and concentration. They found that cognitive state was significantly higher in trilinguals compared to bilinguals, and in multilinguals compared to trilinguals. Another possible reason for the discrepancy between the two studies is that the sample in Kavé et al. (2008) only included older participants (mean age = 83 years). However, these findings are not directly comparable to the results of the present study as the two tests employed by Kavé et al. (2008) give a more general idea of cognitive level than the Simon task. Nevertheless, the result shows the consistent finding of bilingual advantage in older participants and suggests that in terms of inhibitory control and monitoring performance, managing two languages is preferred to three.

The ability of monolinguals in this sample to retain their ability to inhibit irrelevant information whilst responding more slowly with increasing age is a surprising and, therefore, very interesting result, especially in the light of the common finding that inhibitory control decreases and reaction time slows with age (e.g. Proctor et al., 2005) and that older adults are more affected by irrelevant information than younger adults (Tun et al., 2002). The finding that trilinguals' inhibitory control started to significantly decline compared to that of monolinguals and bilinguals, after the age of around 29 years of age is in line with findings of Salthouse (2009a), who reported that some aspects of cognitive functioning begin to decline in early adulthood (in the 20s and 30s).

5.5.4 Methodological considerations

It is unclear why trilinguals were unable to retain the ability to both inhibit irrelevant information and monitor their attention with age. As with the bilingual group, trilinguals were highly and equally proficient in their first two languages. Perhaps their L3 proficiency, which was not tested, influenced their performance on this task. Both groups had various languages as their first, second and third (trilinguals) and came from divergent cultural backgrounds, which may have confounded the results (Hilchey and Klein, 2011). However, if these factors were to blame, surely both bilingual and trilingual groups would have shown a similar pattern with age, not the opposite.

5.5.5 Implications

The unexpected trilingual disadvantage finding in inhibitory control, particularly the observation that trilinguals differed from bilinguals, indicates that if trilinguals (and perhaps multilinguals) are included in a bilingual group they can significantly alter the performance of that group. This may suggest that those studies which have reported similar performance in monolinguals and bilinguals, and have either knowingly or unknowingly included trilinguals or multilinguals in their bilingual group, could have missed a true bilingual advantage.

5.6 Conclusion

By investigating age on a continuum rather than comparing predetermined age groups, a complex relationship was observed among the language groups. The results do not provide supportive evidence that there are advantages of being bilingual or trilingual in terms of inhibitory control and monitoring. On the contrary, they strongly indicate a trilingual disadvantage with age. Moreover, they suggest that previous results on the bilingual advantage may have been confounded by trilingualism, and that future studies will need to control for this.

5.7 Chapter summary of key points

- Previous studies on the effect of bilingualism on EF have demonstrated a bilingual advantage, compared to monolinguals. However, evidence is not entirely conclusive.
- Limited research on trilinguals has been done.
- The proposed bilingual advantage in inhibitory control and monitoring was examined in a sample of monolinguals, bilinguals and trilinguals.
- Age effects were explored on a continuum rather than in predetermined age groups.
- Participants, who ranged in age from 18 to 70 years completed the Simon task. Two important markers were investigated: inhibitory control and monitoring.
- Multivariate GLM analysis showed that age only predicted inhibitory control in trilinguals, but not in monolinguals or bilinguals.
- The analysis also showed that age predicted monitoring in monolinguals and trilinguals, but not bilinguals.
- A trilingual disadvantage was seen in older participants in inhibitory control.
- The results suggest that age affects monolinguals, bilinguals and trilinguals differently with respect to both inhibitory control and monitoring.

- The results further suggest that monolingualism and bilingualism, but not trilingualism, attenuate age-related decline in inhibitory control, whereas bilingualism reduces age-related decline in monitoring.
- Importantly, the present data suggest that including trilinguals in a bilingual sample could have skewed data from previous studies and future studies need to control for a possible confounding effect of having trilinguals or multilinguals in their 'bilingual' cohort.

Some of the information from this chapter can be found in Gudmundsdottir and Lesk (in preparation) 'Trilingual disadvantage in inhibitory control: evidence from ageing'.

Chapter 6: The effects of trilingualism and ageing on working memory capacity

6.1 Introduction

Chapter 5 investigated the effect of trilinguals on cognitive control, deploying the Simon task. A trilingual inhibitory control disadvantage (compared to monolinguals and bilinguals) in adults older than approximately 29 years was reported, but similar performance across language groups in monitoring. This is not in line with some recent studies on bilingualism and cognition which indicate that, compared to monolinguals, bilinguals may have enhanced cognitive control, as measured by non-linguistic tasks, such as the Simon task. It has been proposed that managing two languages requires cognitive control, which in turn leads to a more efficient EF network (for a review, see Bialystok et al., 2012). Initially, the focus was on inhibition as it had been hypothesised that bilinguals attained enhanced inhibitory control due to the continued practice of inhibiting one language whilst using the other (Bialystok et al., 2004; Bialystok et al., 2008; Costa et al., 2008; Martin-Rhee and Bialystok, 2008).

Accumulating evidence has shown that the bilingual advantage may extend beyond inhibition, such as to task-switching (Garbin et al., 2010; Prior and MacWhinney, 2010) and episodic memory (Bak et al., 2014; Zahodne et al., 2014; Ljungberg et al., 2013; Schroeder and Marian, 2012; Wodniecka et al., 2010). Further to this, in a review, Hilchey and Klein (2011) concluded that on interference tasks, such as the Simon task, the bilingual advantage is more reliably found in attentional monitoring (global reaction time) than inhibitory control (incongruent trials minus congruent trials). This suggests that the enhancing effect of managing two languages may not entirely be because of a bilingual's continuous practice of inhibiting the language not in use, but could involve more aspects of cognitive control. According to Miyake and colleagues' theoretical framework (Miyake and Friedman, 2012) inhibition and WM may share underlying mechanisms. If this holds, and the bilingual advantage comprises a more general cognitive control enhancement than that of inhibition, it should also extend to WM.

This chapter investigates whether the bilingual advantage could be extended to trilinguals and WM performance (or, as in line with previous chapter, a disadvantage). This will be measured by a numerical version of the N-back task, in young adults to older adults. As in previous chapter, age will be measured on a continuum rather than in predetermined age groups.

6.1.1 WM and the N-back task

WM involves operations such as maintaining, manipulating and updating relevant information in short term memory, for an on-going cognitive task (Baddeley, 2003). A prominent task used to assess WM is the N-back task (Kirchner, 1958; Chen and Mitra, 2009; Schmiedek et al., 2009a; Shucard et al., 2011). It has been a prominent tool in the fields of clinical, cognitive neuroscience and ageing research (Schmiedek et al., 2014; Redick et al., 2013). In this task, participants are shown a series of stimuli such as letters or words, one at a time, and are asked to decide whether the one that is currently presented matches the stimulus N presentations back. For example, if N = 1, each new stimulus is matched against the stimulus presented immediately previously, and if N = 2 the new stimulus is matched against the stimulus presented two stimuli back, and so on. When performing the N-back task, it is not sufficient simply to maintain a representation of recently presented items; the WM buffer must be updated continually to keep track of what the current stimulus must be compared to. Thus, this task is thought to capture the core of WM, by placing great demands on the key processes associated with WM, namely on-line monitoring, and continual updating and manipulation of information. The reaction time and accuracy rate differences between 0-back and 1-back, 1-back and 2-back trials and so on, are thought to reflect the cost of managing the increased demands on updating (Owen et al., 2005; Jonides et al., 1997).

6.1.2 Bilingualism and WM performance

Thus far, the research examining bilingualism and WM in children has been elusive. Several studies have reported that managing two language systems has little impact on the development of WM abilities in bilingual children (Bonifacci et al., 2011; Engel de Abreu, 2011; Namazi and Thordardottir, 2010; Martin-Rhee and Bialystok, 2008). That is, children with one or more languages performed similarly on the WM tasks. Blom et al. (2014) reported a bilingual advantage in both verbal and visuospatial WM capacity. By contrast, Bialystok (2010) observed a monolingual advantage on a forward digit span task but a similar performance on a backward digit span task (study 3). Similar performance on the forward digit span task was observed in studies 1 and 2 (see Bialystok, 2010 for details). Recent evidence suggests that when complexity of the task is manipulated and as the executive demands of the task increase the greater the bilingual advantage. Morales et al. (2013) reported a bilingual advantage in WM in five to seven year old children, as well as investigating whether this could be tied to other sub-groups of EF, such as inhibition and shifting. They used a Simon-type task (the Simon task with added WM manipulations), and a visuospatial span task (the frogs matrices task – TMT), both of which manipulated WM demands. They found that bilinguals outperformed monolinguals on both WM tasks. On the Simon-type task, bilinguals were better in both the simple and difficult condition, by responding faster to all conditions and showing higher accuracy when responding to incongruent trials. In the visuospatial span task they found that, overall, bilinguals outperformed monolinguals and the more demanding the EF requirements, the larger the difference was between monolinguals and bilinguals.

6.1.3 WM and ageing

It has been demonstrated that WM performance declines with age (Saliasi et al., 2014 – N-back; Cansino, 2013 – N-back; Schmiedek et al., 2009b – N-back; Gazzaley et al., 2005; De Beni and Palladino, 2004; Missonnier et al., 2004; Nyberg et al., 2009 – N-back; Lustig et al., 2001), and evidence indicates that these age differences in WM performance become larger with increasing task difficulty (Cansino, 2013; De Beni and Palladino, 2004; Lustig et al., 2001).

The evidence of the effect of bilingualism on WM performance in adults is no less conclusive than in children. Ratiu and Azuma (2014) compared monolingual and bilingual young adults on an operation span task, a backward digit span task, and a symmetry span task, revealing similar performance. Similarly Bialystok et al. (2008) did not observe a difference in performance in either young or older adults on forward and backward Corsi Block test (taps into visuospatial WM), or the self-ordered pointing task (taps into non-spatial executive WM).

Luo et al. (2013) investigated WM performance on a verbal (word span and alpha span tasks) and spatial (Corsi Block test – forward and backward) WM tasks. Their sample included 157 younger adults (58 monolinguals and 99 bilinguals) and 121 older adults (61 monolinguals and 60 bilinguals). The mean age of younger participants was 21 years while that of the older group was around 70 years. They found bilinguals to outperform monolinguals on the spatial tasks but vice versa on the verbal tasks. They also concluded that for both groups performance declined with age, although bilingualism did not slow down the age-related decline, as was shown in Bialystok et al. (2004) who used the Simon task, with added WM manipulations. Furthermore, they did not find age-related decline to be greater on the complex conditions of the tasks. Bialystok et al. (2014 – study 2) compared young and older monolinguals and bilinguals on the recent probe task. This fairly complex WM task assesses proactive interference in WM, and completing this task is thought to rely on controlled attention. Participants completed both verbal (letters) and non-verbal (figures) versions. The mean age of the young adults was approximately 21 years and older participants' age was approximately 71 years. There were 36 participants in each young age group and 18 in each older age group. Bialystok and colleagues (2014) observed an age-related decline on both tasks, both in terms of accuracy and reaction time, but this did not differ between language groups. They further reported higher accuracy and faster reaction times for bilinguals on the figure task. Thus, both language groups performed similarly on the letter task, where younger participants performed better than the older group. On the figure task, younger participants responded faster than older participants, and bilinguals outperformed monolinguals, where greater difference was observed in older adults. Bilingualism did not modulate the declining effects of age with regard to accuracy.

The observation that, unlike Bialystok et al. (2004), Luo et al. (2013) did not find age-related differences between monolinguals and bilinguals – and Bialystok et al. (2014) only in terms of reaction time, or a difference between easy and complex conditions – may indicate that the tasks used are not measuring the same construct. Previous N-back studies have generally found a difference between easy and more demanding levels of this task with age (Owen et al., 2005).

Using a regression analysis, Soveri et al. (2011) investigated the relationship between age and EF in bilinguals only, aged 30-75 years, with a mean age of 52.8 years. On a non-verbal spatial version of the N-back tasks, the Finnish-Swedish bilinguals' performance (reaction time), measured by the n-back effect (2-back minus 1-back) was not predicted by age. The n-back effect in errors was, however, predicted by age, in that older age resulted in a larger effect. This supports the notion that WM performance declines with age, at least in terms of accuracy, although this needs to be further tested using control groups, such as monolinguals, and trilinguals, to explore whether managing one or three languages affects this age-related decline differently.

6.2 The present study: research aims

The present study investigated important gaps in the literature, specifically: (i) whether the proposed bilingual advantage on a fairly complex WM task (Bialystok et al., 2014) will be observed and extended to a trilingual advantage in another prominent WM task, namely the numerical version of the N-back task (1-back and 2-back). The recent probe task taps proactive interference in WM and, like the recent probe task, the n-back assesses interference, but also employs other executive processes, such as updating, and is thus arguably more complex in nature (Jonides and Nee, 2006). Furthermore, as the N-back task taps into updating of WM, (one of the three components of EF proposed by Miyake and colleagues (Miyake and Friedman, 2012; Friedman et al., 2008; Miyake et al., 2000), it is well-suited to examining WM performance of bilinguals and trilinguals. Lastly, Bialystok and colleagues (2014:703) found a bilingual advantage on a fairly complex WM task, and proposed that this suggests that the *"the bilingual advantage has 'room to emerge' in children, older adults and on relatively complex tasks"* tapping into EF. If this holds true, then a similar pattern is likely to be observed in present study, which utilises a more complex task. (ii) Looking at age on a continuum (rather than between predetermined age groups) will give us a clearer understanding of when exactly the bilingual, and possibly trilingual, advantage starts to emerge in adults. Luo et al. (2013) neither found age-related differences between monolinguals and bilinguals, nor a difference between easy and complex conditions. However, these could be task specific, as Bialystok et al. (2014) observed a greater bilingual advantage in older adults. Previous N-back studies have generally found a difference between easy and more demanding levels of the N-back task with age (Owen et al., 2005).

Based on the literature, a heightened WM capacity with increased number of languages was predicted. That is, trilinguals will show the strongest capacity and monolinguals the weakest.

It was also predicted that all language groups will show an age-related decline in WM capacity, but that bilingualism and to a greater extent trilingualism, will reduce this age-related decline compared to monolinguals.

It was further predicted that these age differences will increase with rising task difficulty, and the differences between the language groups will become larger with age and increased task difficulty.

6.3 Methods

6.3.1 Participants

One hundred and forty two participants (102 females and 40 males), ranging in age from 18 to 79 years (M = 32.96, SD = ±17.49) participated in the experiment, divided into three groups of monolinguals (N = 48), bilinguals (N = 60) and trilinguals (N = 34). On average, participants had spent 16.49 years in education (SD = ±3.41). The same inclusion criteria as in Chapter 5 was applied here. Ethics approval was obtained from the Humanities, Social and Health Science Research Ethics Committee at the University of Bradford and all participants provided informed consent.

Monolinguals

All monolinguals had English as their first language and were functionally fluent (able to hold a conversation) only in English.

Bilinguals

The bilinguals had various languages as their first language, and five had English as their first language. Most bilinguals had English as their second language. The non-English languages were Greek (N = 8), Urdu (N = 7), Punjabi (N = 6), Polish (N = 5), Arabic (N = 4), Estonian (N = 3), Gujarati (N = 2), Hungarian (N = 2), Icelandic (N = 2), Romanian (N = 2), Yoruba (N

= 2), Bemba, Bulgarian, French, German, Hindi, Korean, Maltese, Pashto, Serbian, Somali, Turkish and Twi (N = 1 each).

Trilinguals

Trilinguals had various languages as a first language [Punjabi (N = 9), English (N = 3), German (N = 3), Arabic (N = 2), Guajarati (N = 2), Kurdish (N = 2), Latvian (N = 2), Urdu (N = 2), Bulgarian, Hinko, Icelandic, Indonesian, Kirundi, Polish, Russian, Spanish and Yoruba (n = 1 each)], a second language [English (N = 12), Urdu (N = 5), French (N =3), Swedish (N = 2), Arabic, Betawi, Chinese, Danish, Greek, Hindi, Latvian, Norwegian, Potwari, Punjabi, Russian and Spanish (N = 1 each)] and a third language [English (N = 17), French (N = 2), Russian (N = 2), Punjabi (N = 3), Urdu (N = 6), Arabic, Chinese, Hindi and Spanish (N = 1 each)].

6.3.2 Materials

6.3.2.1 Lifestyle questionnaire

A questionnaire (see Appendix 1) was used to determine demographic information, language use, age, number of years in formal education, country of origin, which languages they spoke and age of L2 AoA, as well as physical and cognitive activity. Further to this, participants provided information on self-rated proficiency in their first language (L1) and second language (L2) on a 5-point scale (1 = very poor to 5 = very good) and language use per day in percentages (L1, L2 and third language (L3)) which totalled 100%.

6.3.2.2 N-back task

Participants performed a computerised sequential-numerical version of the N-back task (Gevins and Cutillo, 1993), where digits from 1 to 9 were presented randomly at the centre of the screen, one at a time. A practice trial preceded each condition and in each of the conditions a total of 90 numbers was presented. Each condition was divided into three blocks of 30 numbers. A brief break was taken between blocks (approximately one minute) and an approximate two to three minute break was taken between conditions. Stimulus duration was 500 milliseconds, with an inter-stimulus interval of 3000 milliseconds. For the 1-back condition, each number was compared with the previously presented number to determine whether it was the same number (match) or not (non-match). For the 2-back condition, each number was compared with the number presented two numbers back. Approximately 30% of the numbers were match numbers and 70% non-match in both conditions. Participants were instructed to press a green key for match stimuli and a red key for non-match stimuli with their dominant hand, and to keep their fingers placed on the keys throughout the experiment. See Figure 6 for a diagram of the task.

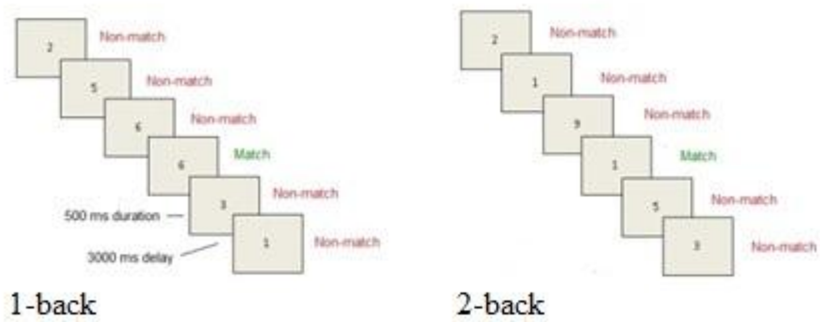

Figure 6. A diagram of the two levels of difficulty in the N-back task; 1-back and 2-back.

6.3.3 Design

A quasi-experimental design was employed, whereby monolinguals, bilinguals and trilinguals were compared on the following measures:

(i) 1-back match, (ii) 1-back non-match, (iii) 2-back match, (iv) 2-back non-match, (v) n-back effect match and (vi) n-back effect non-match. To clarify, (v) and (vi) are calculated as 2-back minus 1-back and are thought to reflect increasing load on WM. Both accuracy and reaction time (RT) measures were looked at.

6.3.4 Procedure

The same procedure as in previous chapter was employed here (see Chapter 5).

6.4 Results

The present study investigated WM in monolinguals, bilinguals and trilinguals.

6.4.1 Characteristics and background measures

Age: monolinguals' mean age was significantly higher than that of bilinguals and trilinguals (both $p < .01$). *Gender:* there were no gender differences in terms of performance. *Education:* trilinguals had spent a trend to significantly ($p = .07$) more years in education than monolinguals (mean difference = 1.7 years). *L2 AoA:* bilinguals ($M = 9.27$ years, $SD = \pm 7.88$) acquired L2 significantly later than trilinguals ($M = 4.61$, $SD = \pm 5.51$). *Balanced language skills:* According to self-assessment bilinguals' L1 ($M = 4.35$, $SD = \pm .90$) and L2 ($M = 4.21$, $SD = \pm .82$) proficiency did not statistically differ, nor did trilinguals' L1 ($M = 4.45$, $SD = \pm .87$) and L2 (M =

4.53, SD = ±.51). *Daily language use:* bilinguals used L2 (mean = 62.32, SD =± 24.61) significantly more than L1 (mean = 36.66, SD = ±24.07 ($p < .001$). Trilinguals used their L3 the most (41.79, SD = ±36.37), which statistically differed ($p < .05$) from L1 use (mean = 23.03, SD = ±51.64), but L2 use (35.18, SD = ±33.45) did not differ from the other two languages (both $p > .1$). SES was indexed by years of education (Emmorey et al., 2008; Bialystok et al., 2008).

6.4.2 Analysis

By definition, the first number of each block for the 1-back and first two numbers of each block for the 2-back were non-match so the responses to these stimuli were not included in the analysis. RTs longer than two standard deviations from the mean were removed for each participant (less than 5%). RTs and accuracy scores (ACC) for successful matches and non-matches were only used in the analysis. The alpha level was set to .05 in all analyses.

Participants responded faster to match trials on 1-back than 2-back ($t(141) = -9.26$), confirming a significant N-back effect (increase in WM load) (M = 136.92 ms). Responses were also faster to non-match trials on 1-back than 2-back, confirming a significant N-back effect (M = 146.93 ms).

The data were submitted to a multivariate general linear model (GLM), with match and non-match n-back effect accuracy (%), 1-back match and non-match accuracy (%) and 2-back match and non-match accuracy (%) as dependent variables with language group (monolinguals, bilinguals, trilinguals) as a fixed factor and age and years of education as covariates. To examine any age effects, an interaction term of language group x age was also included in the model. For simplicity ACC and RT measures were analysed separately, and this method was thus repeated for the RT measures. The language group x age interaction was non-significant for both ACC and RT measures and was therefore taken out of the model.

6.4.3 N-back accuracy

Table 3 indicates a decline in accuracy with increased task difficulty across the language groups [1-back (mean = 92.75 %), 2-back (mean = 89.09 %), t (141) = 5.61, p <.001] and that, overall, participants responded more accurately to non-match than match stimuli.

Table 3. Mean accuracy scores (%) and ±SDs (in parentheses) for 1-back, 2-back and the n-back effect (match = m; non-match = nm) by language group

	Monolinguals	**Bilinguals**	**Trilinguals**
1-back (m)	89.6 (8.76)	88.4 (12.15)	88.71 (10.91)
1-back (nm)	96.92 (2.72)	96.33 (3.59)	96.5 (4.01)
2-back (m)	88.73 (9.32)	83.02 (18.65)	82.15 (14.97)
2-back (nm)	94.27 (3.89)	94.43 (4.67)	91.94 (6.44)
n-back effect (m)	-0.88 (8.7)	-5.38 (16.98)	-6.56 (13.77)
n-back effect (nm)	-2.65 (4.04)	-1.9 (4.5)	-4.56 (6.1)

After adjustment for age and education, the multivariate GLM analysis revealed a main effect of language group on 2-back match (F (2,137) = 3.32, p < .04) and n-back (non-match) effect (F (2, 137) = 3.36, p < .04). To investigate this further, data were submitted to a univariate GLM which revealed no statistical difference between the groups for 2-back match, but did so for n-back effect (non-match), with pairwise comparisons revealing a significant difference between trilinguals and bilinguals, whereby trilinguals' n-back effect (non-match) was significantly larger (p < .04). There was no main effect of age.

6.4.4 N-back reaction time

Figure 7 shows that participants took shorter time to respond to stimuli in 1-back (M = 591.32ms) than in 2-back (M = 735.80ms), t (141) = -9.57, p <.001), and longer to respond to non-match than match stimuli, in both 1-back and 2-back. In all 1-back and 2-back measures RT increased with increasing number of languages [SEs: 1-back (match): ML = ±18.89, BL = ±16.27, TL = ±21.76; 1-back (non-match): ML = ±19.30, BL = ±16.62, TL = ±22.23; 2-back (match): ML = ±30.94, BL = ±26.64, TL = ±35.64; 2-back (non-match): ML = ±35.86, BL = ±30.88, TL = ±41.30)].

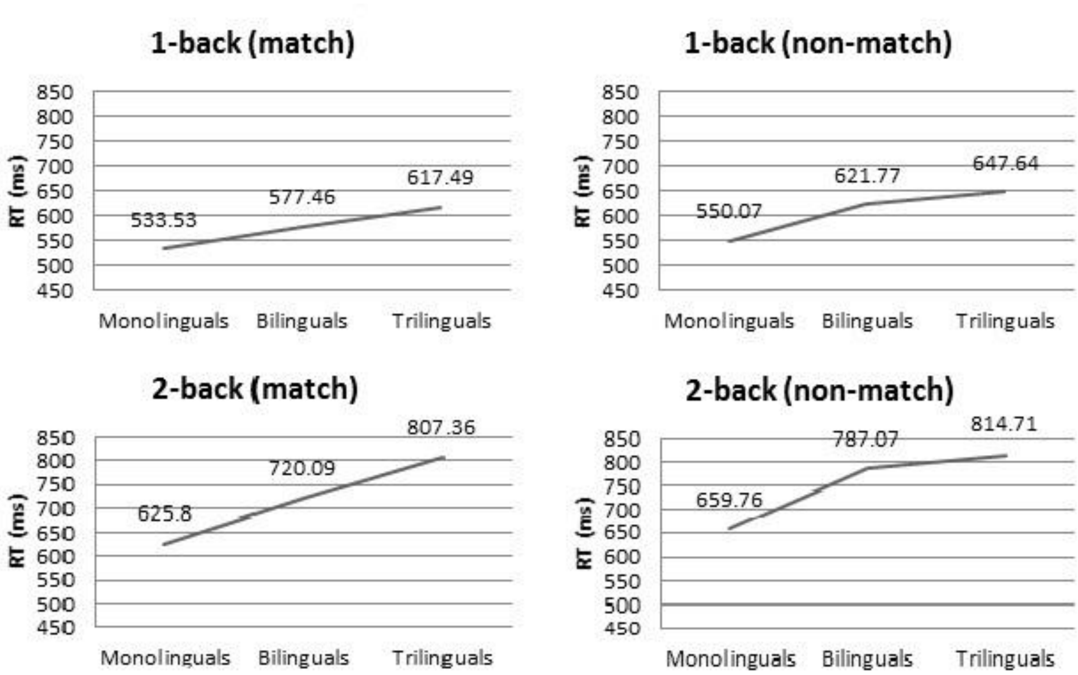

Figure 7. Mean reaction times (adjusted means) for 1-back and 2-back measures (match and non-match) by language group.

Both n-back effects became larger with increasing number of languages (see Figure 8).

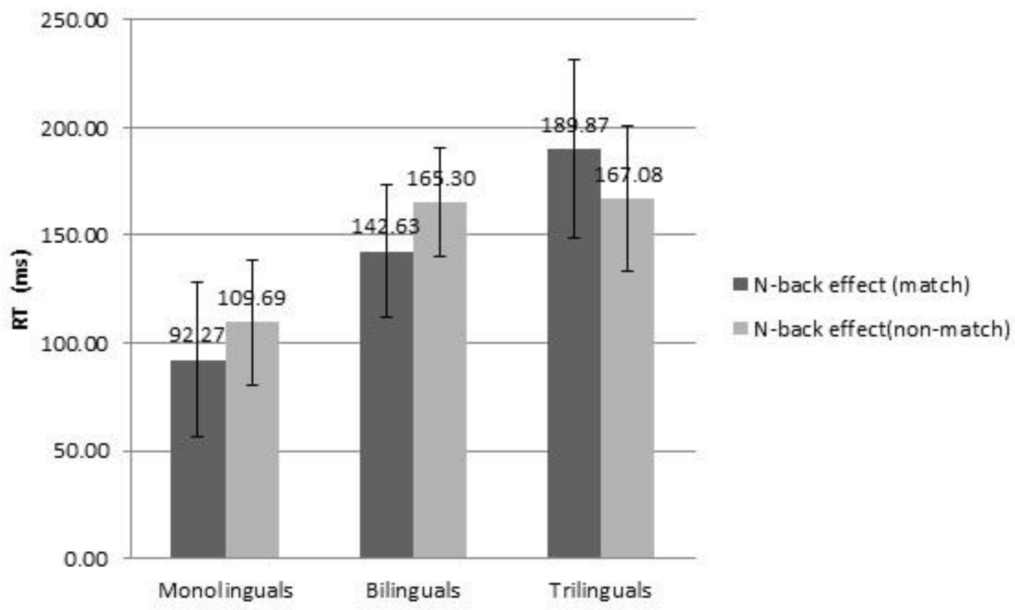

Figure 8. Mean reaction times (adjusted means) and ±SEs for the n-back effects (match and non-match differences between 1-back and 2-back) by language group.

The multivariate GLM RT analysis revealed a main effect of age on all six measures (all = $p < .001$), and a main effect of language group on 1-back match ($F(2,137) = 4.05$, $p < .02$), 1-back non-match ($F(2,137) = 5.95$, $p = .003$), 2-back match ($F(1,137) = 7.06$, $p = .001$), 2-back non-match ($F(2,137) = 4.75$, $p = .01$), and marginally on n-back effect match, ($F(2,137) = 2.96$, $p = .055$). The only measure that did not reach significance regarding language group was the n-back effect non-match.

6.4.5 Main effect of language group

Separate univariate GLMs were conducted to assess the main effect of language group on the n-back RT measures, with pairwise comparisons revealing, after adjusting for age and education, that monolinguals responded significantly faster than trilinguals to 1-back match ($p < .02$), faster than bilinguals ($p = .02$) and trilinguals ($p = .005$) to 1-back non-match, marginally faster than bilinguals ($p = .078$) and faster than trilinguals ($p = .001$) to 2-back match, faster than bilinguals ($p < .03$) and trilinguals ($p <.03$) to 2-back non-match and showed a smaller n-back effect (match) than trilinguals ($p < .05$). The differences between bilinguals and trilinguals did not yield a statistical significance.

6.4.6 Age effects and RT

Unlike accuracy measures which revealed no effect of age, Figure 9 suggests that age predicted RT performance in both the 1-back and 2-back conditions and the n-back effect (match and non-match). The association is slightly stronger in the 2-back than the 1-back condition, indicating a decline in the capability of dealing with the increased WM load with age.

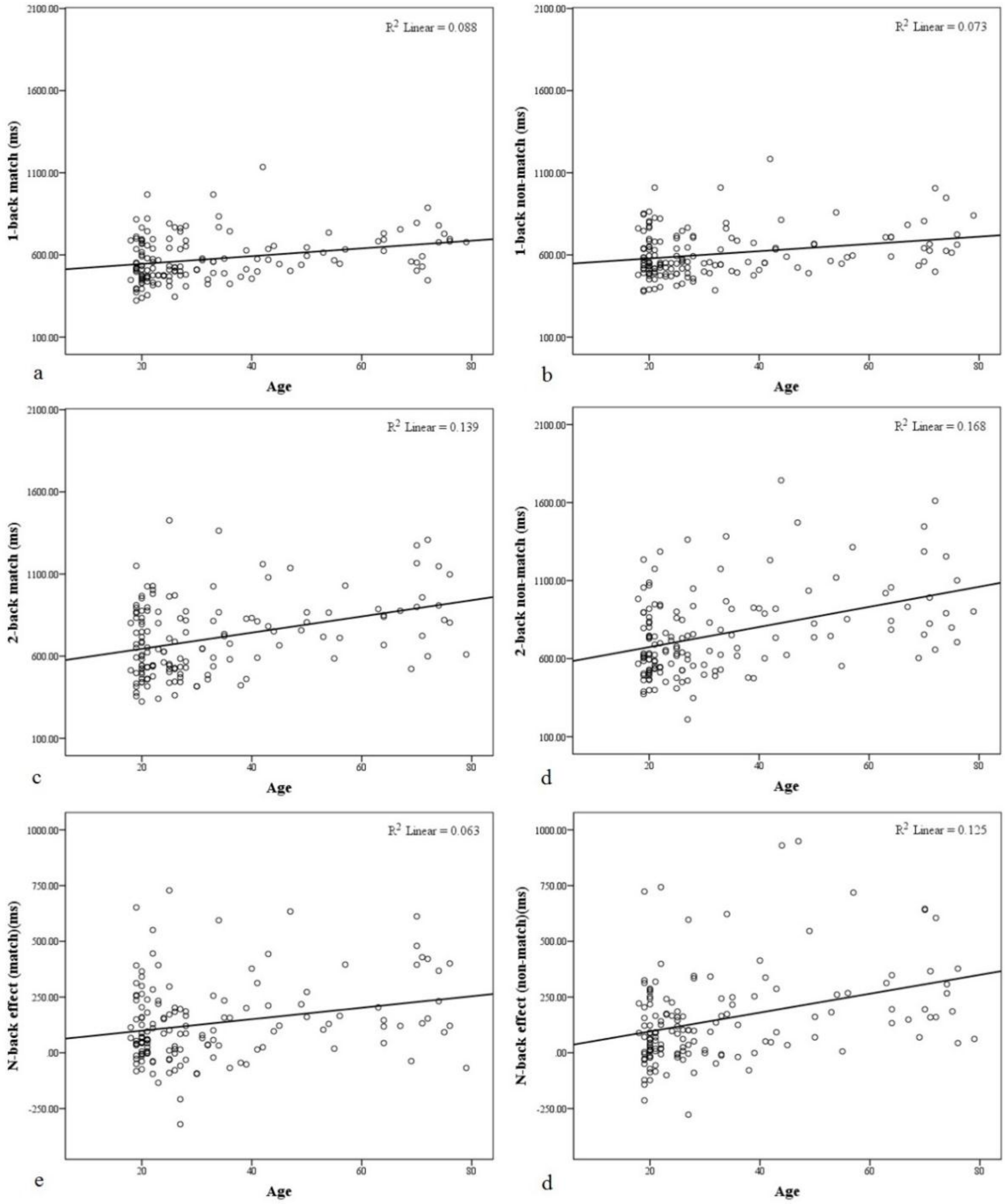

Figure 9. Scatterplots depicting the relationship between age and the 1-back measures (a and b), the 2-back measures (c and d) and the n-back effect (e and f).

Separate regression analyses were conducted for each measure, with age as the independent factor, revealing a moderate positive linear, and highly significant relationship between age and all six measures [1-back (match): (β = 493.75, (F (1, 140) = 14.96, p < .001), y axis intercept = 2.38 with regression correlation coefficient r = .31, p < .001), 1-back (non-match): (β = 530,33, (F (1, 140) = 12.19, p = .001), y axis intercept = 2.23 with regression correlation coefficient r = .28, p < .001), 2-back (match: (β =

547.33, ($F(1, 140) = 23.00$, $p < .001$), y axis intercept = 4.91 with regression correlation coefficient $r = .38$, $p < .001$), 2-back (non-match): ($\beta = 535.27$, ($F(1, 140) = 31.31$, $p < .001$), y axis intercept = 6.53 with regression correlation coefficient $r = .43$, $p < .001$), n-back effect (match): ($\beta = 53.58$, ($F(1, 140) = 9.41$, $p = .003$), y axis intercept = 2.53 with regression correlation coefficient $r = .25$, $p = .001$) and n-back effect (non-match): ($\beta = 4.93$, ($F(1, 140) = 21.83$, $p < .001$), y axis intercept = 4.31 with regression correlation coefficient $r = .37$, $p < .001$)]. This confirms age as significant predictor of RT performance, with a stronger relationship with age as load increases. However, as stated above, the interaction between language group and age was non-significant, indicating that age was not modulated by language group.

6.4.7 Summary of N-back data

In summary, in terms of accuracy (which was not affected by age) the accuracy of response decreased with increased difficulty (n-back effect) but this only differed in the non-match n-back effect, whereby bilinguals showed a smaller effect. Apart from this, accuracy was similar among the groups. Reaction time, however, increased with age for all n-back measures, but age was not modulated by language group. Overall, monolinguals responded faster than trilinguals in both 1-back and 2-back (both match and non-match), and showed a smaller n-back effect (match) than trilinguals. Monolinguals also outperformed bilinguals in 1-back non-match, 2-back non-match and marginally in 2-back match. There was no difference between bilinguals and trilinguals in terms of RT.

6.5 Discussion

This chapter tested whether the bilingual advantage in WM performance would extend to trilinguals and become more enhanced. A numerical version of the N-back task was used, which, to the author’s knowledge, has not been employed before in the study of cognition and bilingualism/trilingualism. Based on previous literature, it was hypothesised that performance would improve with increasing number of languages, and that these language group differences would become greater with increased level of task difficulty. Further to this, by looking at overall change across age, it was hypothesised that the expected age-related decline in WM performance would be reduced in bilinguals, and to a greater extent in trilinguals, compared to monolinguals.

6.5.1 Main findings

Contrary to the present chapter's predictions the RT results clearly revealed a bilingual and trilingual ***disadvantage***, compared to monolinguals. Although the data indicate a gradual decrease in performance with increasing number of languages, the difference between bilinguals and trilinguals did not yield significance. There were no language group differences in the observed age-related decline. In terms of accuracy all groups performed similarly, albeit trilinguals were statistically significantly outperformed by bilinguals on the n-back (non-match) effect.

From this experiment it is unclear why more languages should be having a negative effect on this type of WM test. Numbers were chosen as stimuli to minimize linguistic interference, as, compared to monolinguals, bilinguals have been observed to have a smaller vocabulary in both their languages (Bialystok et al., 2010 – children; Bialystok and Luk, 2012 – adults), be slower (Ivanova and Costa, 2008; Costa and Santesteban, 2004) and less accurate (Gollan et al., 2007) to name pictures on picture naming tasks. However, a bilingual advantage has been observed on verbal cognitive tasks, such as an episodic memory task (Zahodne et al., 2014) and a WM task (Blom et al., 2014), and similar performance between monolinguals and bilinguals on a verbal WM task (Ratiu and Azuma, 2014). This indicates that verbal material used in cognitive tasks may not always cause linguistic interference. Nonetheless, there is evidence for distinct neural systems of letter and numerical recognition (Park et al., 2012). With regard to WM, Knops et al. (2006) demonstrated in an fMRI investigation, using the N-back task, that numerical and verbal stimuli activated slightly disparate areas in the intraparietal sulcus, suggesting that the processing of these two types of stimuli is not entirely the same. The IPS is employed during tasks requiring controlled attention (Greenberg et al., 2012), maintenance and manipulation in WM (Bray et al., 2013; Champod and Petrides 2010, 2007). However, it is difficult to conduct research that completely erases any potential linguistic interference.

Nevertheless, a bilingual advantage in EF has been previously reported using numerical stimuli. For example Hernández et al. (2010) observed a bilingual advantage on a numerical version of the Stroop task, where bilinguals demonstrated a smaller Stroop interference effect and larger Stroop facilitation effect, and were marginally faster than their monolingual counterparts. Furthermore, Bialystok et al. (2008) reported a bilingual advantage on a Stroop colour naming task (reduced interference), despite being outperformed by their monolingual counterparts on linguistic measures. The same groups of participants performed similarly on forward and backward Corsi Block test. Interestingly, having controlled for language proficiency differences between monolinguals and bilinguals in their sample, Luo et al. (2013) still found a bilingual disadvantage in verbal WM, indicating that there may well be other potential influencing factors at play.

6.5.2 Bilingual and trilingual disadvantage

The novel finding that bilinguals, and to a greater extent trilinguals, were outperformed by monolinguals contrasts with earlier findings of the advantageous effect of bilingualism on inhibition (Bialystok et al., 2004; Bialystok et al., 2008; Costa et al., 2008; Martin-Rhee and Bialystok, 2008), and other executive processes such as task-switching (Garbin et al. 2010; Prior and MacWhinney, 2010), episodic memory (Schroeder and Marian, 2012), WM, as measured by Corsi blocks (Luo et al., 2013), and on a proactive WM task (Bialystok et al., 2014). The recent probe task applied by Bialystok and colleagues (2014) is arguably more complex than other tasks that have been previously used to investigate the bilingual advantage. This may explain, for example, why Ratiu and Azuma (2014) did not report any difference between young adult monolinguals and bilinguals on three types of span tasks (operation span task, backward digit span task and symmetry span task). That is, if it holds true that the bilingual advantage is more likely to emerge on complex tasks in adults (Bialystok et al., 2014). In children, a bilingual advantage was observed in two types of WM tasks; a visuospatial task and a Simon task with added WM manipulation (Morales et al., 2013). It is noteworthy, however, that some studies did not find any group differences (between monolingual and bilingual children) on various WM tasks (Namazi and Thordardottir, 2010; Engel de Abreu, 2011; Engel de Abreu et al., 2012). The bilingual and trilingual disadvantage reported here does, however, fit with new evidence by Paap et al. (2014), who reported a bilingual and trilingual disadvantage, compared to monolinguals, in the Simon task (greater Simon effect). The Simon task is thought to tap into the inhibition component in Miyake and colleagues' (Miyake and Friedman, 2012; Friedman et al., 2008; Miyake et al., 2000) model of EF, in which inhibition and updating are considered to correlate with one another (as well as shifting).

6.5.3 WM and age effects

As expected, RTs slowed down with age, which fits the generally known age-related slowing in processing speed (Salthouse, 2000), and is also in line with WM age-related decline (Saliasi et al., 2014 – N-back; Cansino, 2013 – N-back; Schmiedek et al., 2009 – N-back; Gazzaley et al., 2005; Nyberg et al., 2009 – N-back; Missonnier et al, 2004), as well as with findings in the bilingualism literature (Bialystok et al., 2014; Luo et al., 2013; Bialystok et al., 2004). An age-related decline was not seen in terms of accuracy. This could be explained by the fact the sample did not include elderly persons above 79 years (and included more younger vs. older participants). Perhaps accuracy starts to decline later in life than RTs, at least in the present sample. This argument can be supported by evidence, such as from Wild-Wall et al. (2011), who compared young (19-31 years) versus middle aged (48-59 years) on N-back performance (2-back), and found that age-related decline was only observed in RTs. This finding echoes the observation that existing evidence for when and how WM performance starts to decline in adulthood is inconclusive (Cansino et al., 2013). The finding that the language groups did not differ in age-related decline matches that of (Luo et al., 2013), and suggests that the differences seen between monolinguals and bilinguals, and trilinguals were consistent across the age span from 18 to 79 years. This finding contradicts the results of Bialystok et al. (2014; 2004), who found that bilinguals slowed down the age-related decline compared to monolinguals.

6.5.4 Methodological considerations

The bilingual and trilingual participants had various languages as their first, second and third, and came from different cultural backgrounds. This may have influenced the scores (Hilchey and Klein, 2011), although it can be argued that this variability could be seen as a control for any potential confounding effects of language and cultural backgrounds. Supporting this view is the fact that both Luo et al. (2013) and Bialystok et al. (2014) reported a bilingual advantage, despite employing bilinguals from various cultural and language backgrounds.

Another possible confounding effect could be that some of the non-English languages, such as Hindi, Punjabi and Urdu, do not use the same numerals as English. However, many of the participants (most of whom had lived in the UK from birth and were second or third generation immigrants) who spoke these languages reported only speaking the language, but not reading or writing it. Therefore, it is possible that those participants' performance was not affected by this factor.

6.6 Conclusion

The results of this chapter have demonstrated an overall bilingual and trilingual disadvantage in WM performance, but in terms of ageing the three language groups performed mostly similarly. The results provide a novel contribution to the knowledge of how trilingualism and bilingualism negatively impact WM performance. Further research needs to examine lower and higher levels of complexity of the N-back task, to examine where the boundaries of the bilingual, and perhaps the trilingual, advantage lie in terms of complexity.

6.7 Chapter summary of key points

- Previous studies have demonstrated a bilingual advantage in various domains of EF, such as inhibition and task-switching, and episodic memory.
- Limited work has been done on WM performance, comparing monolingual and bilingual adults, although a recent study demonstrated a bilingual advantage on a fairly complex WM task (Bialystok et al., 2014).
- Limited work has been done in trilingual adults.
- In this study, to investigate WM in monolinguals, bilinguals and trilinguals, participants completed a numerical version of the N-back task, which to the author's knowledge has not been used before in this context.
- The N-back task was more complicated than the one used by Bialystok et al. (2014) and taps into more areas of WM, such as the updating component.
- Age was examined on a continuum, unlike previous studies, which examined its effects using predetermined age groups.
- Overall, the language groups did not differ in terms of accuracy of response, although a trilingual disadvantage was observed in comparison to bilinguals on the n-back effect (non-match).
- In terms of reaction time, there was an overall bilingual and trilingual disadvantage, compared to monolinguals.

- Figure 7 indicates a gradual decrease in performance with increasing number of languages, but the differences between bilinguals and trilinguals did not yield significance.
- Age did not predict accuracy, but an age-related decline was observed in reaction time, which did not differ between the language groups.
- These results suggest that managing two or three languages, compared to just one, has a negative effect on WM performance.
- Further research is required to fully establish this novel effect of bilingualism and trilingualism on WM performance and its importance in the wider field of cognitive reserve.

Some of the information from this chapter can be found in Gudmundsdottir and Lesk (in preparation) ‘Bilingual and trilingual disadvantage in WM performance’.

Chapter 7: Trilingualism and ageing on inhibition of return

7.1 Introduction

As previously mentioned in this thesis, one of the key components of EF is inhibition; the ability to control irrelevant or unwanted responses (Miyake and Friedman, 2012; Friedman et al., 2008; Miyake et al., 2000). Chapter 5 investigated the cognitive control network, more specifically inhibition and monitoring in the Simon task, and reported a trilingual inhibitory control disadvantage, compared to monolinguals and bilinguals, with increasing age.

Spatial inhibitory processing, which is involved in the control of visual attention, is often referred to as inhibition of return (IOR) (Posner and Cohen, 1984). A recent study (Colzato et al., 2008) indicates that this network may be affected by bilingualism, although another study (Hernández et al., 2010) did not find such effects (see below for more detail).

It is widely accepted that at least three systems of attention exist in the brain, which are both anatomically and functionally autonomous: the alerting network, the orienting network and the cognitive control network (Fan et al., 2009, 2005, 2002). The roles of these networks have been explained as maintaining a general state of activation of the cognitive system, by increasing vigilance to looming stimuli (alerting network), to monitor and resolve conflicts among competing processes (such as choose the right language for the right context and suppress the irrelevant language), in order to achieve goals (cognitive control network), and to selectively allocate the focus of attention to a potential object or area in the visual field (orienting network) (Fan et al., 2009). The orienting network will be focused on in the present chapter.

Although these three networks are believed to be anatomically and functionally separate, research suggests they do interact in various ways

(Chen et al., 2010; Vivas et al., 2007; Raz, 2004; Vivas and Fuentes, 2001). For example, by combining the Stroop and IOR tasks, Vivas and Fuentes (2001) reported that the Stroop effect was affected by IOR, suggesting interacting underlying mechanisms. There is also existing evidence for interaction between IOR and the Simon effect (Wang et al., 2013; Ivanoff and Klein, 2002).

Given that the literature suggests there is cross-talk between the cognitive control network and orienting network, and some evidence suggests an effect of bilingualism on the orienting network, the next logical step is to see if there is any influence of trilingualism here too. I am not aware of any studies exploring the effect of trilingualism on IOR (prior to the start of this project) and since existing literature on the effect of bilingualism is not conclusive, and may be confounded by trilingualism, exploring possible effects of trilingualism is important. Again, as EFs are affected by age (Grady, 2012; Reuter-Lorenz and Park, 2010; Takio et al., 2009; Kray et al., 2004; Zelazo et al., 2004) and given effects of age seen in Chapters 5 and 6 any exploration of the IOR task should include age as a covariate.

7.1.1 Inhibition of return (IOR)

Inhibition of return (IOR), an inhibitory effect, was first reported by Posner and Cohen (1984), using an exogenous spatial cueing paradigm. This paradigm has been used extensively in both research settings (for example Atkinson et al., 2014; Welsh et al., 2009) and in clinical settings (for example Bartolomeo et al., 2012; Mushquash et al., 2012). On a typical spatial cueing detection task, participants press a response button upon detection of a target. The target can either appear in a box on the left side of the screen or on the right side of the screen. Preceding the target an exogenous cue (for example a brightening of one of the boxes) is presented, with the purpose of catching the participant's attention. This cue can either appear in the same location as the target (cued) or in the opposite location (uncued). Posner and Cohen (1984) found that when the time interval between the cue and the target [stimulus onset asynchrony (SOA)] is short (less than about 200-300 ms) responses are faster when the target appears at the cued locations, than in the uncued locations. That is, facilitation occurs. When the time interval between the cue and the target becomes longer the opposite pattern is seen; responses to targets at the cued locations are slower than at the uncued locations; this is known as the inhibition of return effect, or the IOR effect (Klein, 2000), which can last up to at least three seconds (Samuel and Kat, 2003). It has been suggested that IOR reflects a bias against returning attention to previously attended locations, by suspending both motor responses (eye movements) and the return of attention, which increases the efficiency of visual search (Wang et al., 2013; Tian et al., 2011; MacDonald et al., 2009; Klein, 2000).

7.1.2 The effect of bilingualism on IOR and related measures

Colzato et al. (2008) compared monolinguals and bilinguals' performance on the orienting network, measured by the inhibition of return (IOR) paradigm (Posner and Cohen, 1984). They were particularly interested in the IOR effect, given that it is thought to tap into a similar type of enhanced inhibitory control ability that bilinguals had been reported to have in some previous studies (for example Bialystok et al., 2008; Costa et al., 2008; Martin-Rhee and Bialystok, 2008; Bialystok et al., 2004). They compared 18 monolinguals and 18 young adult bilinguals, who were matched for age (mean age = 20.5 years). According to self-report the bilinguals were balanced in both languages. Interestingly, Colzato et al. (2008) did not find a bilingual advantage in global RT (monitoring), and in fact, both language groups responded at a similar speed. As bilinguals had previously been found to outperform monolinguals in inhibitory control the authors expected that both language groups would show similar performance at the short SOAs (i.e. a similar magnitude of the facilitation effect) but that bilinguals would show a larger IOR effect at longer SOAs. Neither pattern was found but they did find that the cueing effects affected the two language groups differently; bilinguals did not show facilitation effects at short SOAs, and at long SOAs IOR effects were only seen in bilinguals.

Hernández et al. (2010) compared young adults (mean age = 20.55 years) in the IOR task (experiment 2), where participants were divided into two groups of 28 Spanish monolinguals and 28 early and high-proficient Catalan-Spanish bilinguals. The bilinguals had received their education in both languages. According to self-report the bilinguals used Catalan considerably more across their lifespan. The two language groups did not differ in age and were matched for general intelligence (Raven‘s Advanced Progressive Matrices) and video-game experience. Hernández et al. (2010) did not report any language group differences in global reaction time or in cueing effects. Thus, the groups did not manifest the same cueing effect patterns as in Colzato et al. (2008), with both groups showing the same magnitude of cueing effects in the short and long SOAs.

Two other studies investigated the orienting network and bilingualism, but deployed different tasks (Costa et al., 2008 – attention network test; Tao et al. (2011) – laterized attention network test (also assesses hemispheric asymmetry)). Unlike Colzato et al. (2008) and Hernández et al. (2010) they both observed a bilingual advantage in global RT. In the case of Tao et al. (2011), only early bilinguals showed an advantage over monolinguals. In terms of orienting, Costa et al. (2008) did not observe between-group differences. Tao et al. (2011), did not find between-group difference in orienting benefit (the difference between a valid cue and a center cue and reflects the efficiency of orienting), but found greater orienting cost (the difference between an invalid cue and center cue, reflecting the efficiency of reorienting) for late bilinguals compared to monolinguals. That is bilinguals were slower than monolinguals to reorient their attention to a target which appeared in an invalidly cued loaction. The authors suggested this may indicate that *“late bilinguals have a greater capacity to inhibit stimuli that occur in an invalid location, which helps them to use the predictive cue more efficiently by filtering out the uncued stimuli in the anticipatory period“* (Tao et al., 2011:16).

In summary, evidence from previous studies is inconclusive, Tao et al. (2011) observed an advantage in late bilinguals, whilst Costa et al. (2008) and Hernández et al. (2010) observed no language group differences, and Colzato et al. (2008) reported that the cueing effects (facilitation and IOR) were differently affected by language group, but did not report a difference in global RT.

7.1.3 IOR and ageing

Inhibitory control is generally assumed to decline with age (Proctor et al., 2005; Van der Lubbe and Verleger, 2002). In line with this assumption, global RT in the IOR task typically declines with age in healthy individuals (McLaughlin et al., 2010; Poliakoff et al., 2007; Bao et al., 2004; Castel et al., 2003; McCrae and Abrams, 2001), although Langley et al. (2001) reported similar global RTs among young and older adults. However, the literature on the effects of ageing on the cueing effects is inconsistent. For example, some studies (Castel et al., 2003; Langley et al., 2001) observed no change with ageing in IOR effects, whilst other studies reported an age-related increase in IOR effects (McLaughlin et al., 2010; Poliakoff et al., 2007; Bao et al., 2004; McCrae and Abrams, 2001).

7.2 Present study: research aims

The overall aim of this chapter is to extend Hernández et al.'s (2010) investigation into the effect of bilingualism in the IOR task, by adding trilingualism and age into the investigation. Both variables that as far as I am aware have not yet been investigated but have the potential to influence this task. The effect of trilingualism on the orienting network will be investigated by comparing monolinguals, bilinguals and trilinguals on an IOR task. As previous findings on the comparison of monolinguals and bilinguals in the IOR task are inconclusive, adding trilinguals might help determine the effect of managing different languages on the orienting network. Importantly, this provides new evidence of the potential effect of trilingualism. Due to the inconclusive findings on IOR and bilingualism so far and in light of the trilingual disadvantage findings in previous chapters of this study (Chapter 5 in particular) it is difficult to predict the direction of differences. However, if it is assumed that IOR taps into similar executive processes as the Simon (e.g. for example Bialystok et al., 2008; Costa et al., 2008; Martin-Rhee and Bialystok, 2008; Bialystok et al., 2004) then a trilingual disadvantage can be expected.

The second main aim of the present chapter is to explore the effect of age. The present study examines age on a continuum rather than comparing groups of young and older adults. Previous studies investigating bilingualism and the orienting network have only been examined in young adults. This may explain the inconsistent findings. As seen previously in this thesis (Chapter 5), the bilingualism/cognitive control literature indicates that a bilingual advantage is more consistently seen in older adults than young adults. As previous evidence (outside the realms of bilingualism) on the effect of ageing is conflicting, it is difficult to predict the direction and how ageing and language groups interact on this task.

7.3 Methods

7.3.1 Participants

Seventy-seven participants (49 females and 28 males) participated in this experiment and were divided into three groups of monolinguals (N = 31), bilinguals (N = 31) and trilinguals (N = 15). Their age ranged from 18 to 79 years (M = 39.45, SD = ±20.70), and on average they had spent 16.12 years (SD = ±3.90) in education.

<u>Monolinguals</u>

Monolinguals were included if they had English as their first language, and were functionally fluent (able to hold a conversation) only in English.

Bilinguals

Bilinguals were included if they spoke two languages on a regular basis. They had various languages as their first language (two participants had English as their first language) and most had English as their second language. The non-English languages were Arabic (N = 4), Greek (N = 4), Urdu (N = 4), Icelandic (N = 2), Polish (N = 2), Romanian (N = 2), Bemba, Bulgarian, Estonian, French, Gujarati, Hungarian, Korean, Punjabi, Serbian, Somali and Twi (N = 1 each).

Trilinguals

Trilinguals were included if they spoke three languages on a regular basis. They had various languages as their first, second and third. First languages were Punjabi (N = 5), Latvian (N = 1), Arabic, Icelandic, Indonesian, German, Latvian, Polish, Russian, Urdu, Yoruba (N = 1 each). Second languages were English (N = 4), Urdu (N = 2), Betawi, Chinese, Greek, Hindi, Latvian, Norwegian, Punjabi, Russian and Swedish (N = 1 each). The third languages were English (N = 9), French (N = 2) Chinese, Hindi, Russian, Spanish (N = 1 each).

All participants had normal or corrected to normal vision, and over 65s did not have an existing diagnosis of cognitive impairments or difficulties. Due to the nature of this study, second language acquisition could be from birth and onwards. The same recruitment process as in the previous chapters was applied here. Ethics approval was obtained from the Humanities, Social and Health Science Research Ethics Committee at the University of Bradford and all participants provided informed consent.

7.3.2 Materials

7.3.2.1 Lifestyle questionnaire

A questionnaire (see Appendix 1) was used to determine demographic information, language use, age, number of years in formal education, occupational status, country of origin, which languages they spoke and age of L2 AoA, as well as physical and cognitive activity. Further to this, participants provided information on self-rated proficiency in their first language (L1) and second language (L2) on a 5-point scale (1 = very poor to 5 = very good) and language use per day in percentages (L1, L2 and third language (L3)) which totalled 100%.

7.3.2.2 Picture naming task (PNT)

Subjective and objective measures of language proficiency have been found to correlate (Luk and Bialystok, 2013; Marian et al., 2007). Nevertheless, an objective language proficiency measure was also employed here, to assess whether trilinguals and bilinguals would show similar proficiency on objective and subjective measures. Snodgrass and Vanderwart's (1980) picture naming test was used to objectively assess language proficiency. A total of 80 black and white picture stimuli were randomly chosen from Snodgrass and Vanderwart's picture database. The picture stimuli were presented on a computer screen. Participants were instructed to fixate on a central cross ('+') which was present at the beginning of each trial (duration 1000 milliseconds). When the cross disappeared a picture appeared in the middle of the screen and remained until a response had been made. Participants were instructed to name each picture aloud and press the 'X' key simultaneously if they knew what the picture was showing, and the '.' key if they did not know what the stimuli depicted. Monolinguals completed the test once in their language, bilinguals in their first and second language, and trilinguals in their first, second and third language. The pictures were presented at random, and to prevent order effects, bilinguals' and trilinguals' tests were counterbalanced, so that half of bilinguals completed the test in the order of L1 and then L2 and the other half vice versa. For trilinguals, around three participants were assigned to each of the following conditions: 1 (L1, L2, L3), 2 (L1, L3, L2), 3 (L2, L1, L3), 4 (L2, L3, L1), 5 (L3, L1, L2) and 6 (L3, L2, L1).

7.3.2.3 IOR

This detection task was presented on a computer screen. The task consisted of 40 trials in total. Participants were asked to fixate on a central cross ("+") which was present at the beginning of each trial (duration 1000 milliseconds (ms)). Following this, two grey boxes appeared one to the left and one to the right. Either box was then briefly highlighted (50 ms), to indicate to which side of the screen the participant is to covertly attend. This cue was then followed by an asterisk in either box. The time interval between the cue and target was either 100 ms or 400 ms SOAs. The target was present in 32 trials (16 trials for each SOA condition). To discourage anticipated responses no asterisk followed the cue on eight trials, in which case participants were instructed not to respond. On cued trials the asterisk appeared in the previously highlighted box. On uncued trials, the asterisk appeared in the box which was not previously highlighted. Participants were instructed to respond as quickly as possible when they saw the target, by pressing the 'b' key. See Figure 10 for an example of a trial on this task.

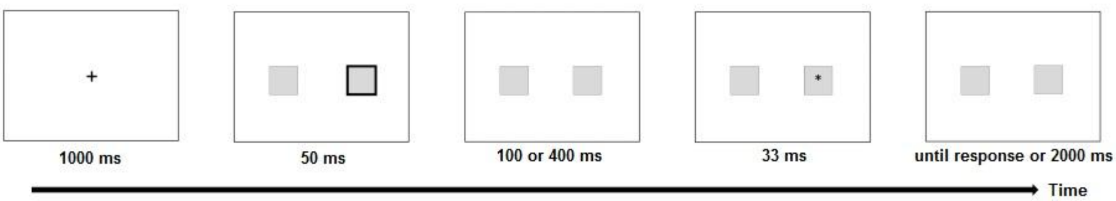

Figure 10. Experimental trial sequence of a cued trial. On an uncued trial the box (left or right) is not briefly highlighted (second screen from left).

7.3.3 Design

The present study employed a quasi-experimental design. Monolinguals, bilinguals and trilinguals were compared on the following accuracy (ACC) and reaction time (RT) measures:

(i) global (monitoring), (ii) short cueing effect (facilitation) and (iii) long cueing effect (IOR). For clarification (i) is calculated as an overall reaction time of the task and (ii) and (iii) are calculated as uncued minus cued. These three variables will be focused on as the fundamental purpose of this chapter is to investigate the effects of monolingualism, bilingualism and trilingualism: that is, cueing effects, IOR in particular, as well as global performance.

7.3.4 Procedure

The same procedure as for previous chapters (see Chapter 5) was employed in the present study. In addition, all participants completed the tasks in the same order.

7.4 Results

The aim of the current chapter was to investigate monolinguals, bilinguals and trilinguals' performance on the orienting network using an IOR task at two SOAs (100ms or 400ms)

7.4.1 Characteristics and background measures

There were no gender differences in terms of performance. Table 4 presents characteristics and background measures for monolinguals, bilinguals and trilinguals. Significance levels between group differences can be seen on the far right.

Table 4. Mean scores, standard deviations (±SDs) and significance levels for main demographic by monolinguals (ML), bilinguals (BL) and trilinguals (TL)

Characteristics	Monolinguals	Bilinguals	Trilinguals	Between group differences
Age	47.35 (23.39)	34.58 (17.36)	30.93 (13.74)	ML vs. BL ($p<.04$), ML vs. TL ($p<.03$), BL vs. TL NS*
Years of education	14.94 (3.99)	17.23 (3.58)	16.67 (3.75)	BL vs. ML ($p=.059$), ML vs. TL and BL vs. TL NS.
Occupational status**	3.80 (1.23)	4.5 (1.03)	3.1 (1.17)	NS

*NS = non-significant, **Occupational status: The three language groups did not differ in occupational status ($p > .05$), which was measured on a 5 - point scale (1 = unemployed, 5 = professional and managerial). The thirty five students (monolinguals = 11, bilinguals = 15, trilinguals = 9) were not included in the occupational status analysis.

Table 5 outlines language background measures for monolinguals, bilinguals and trilinguals.

Table 5. Mean scores, standard deviations (±SDs) for language background measures by language group

Characteristics	**Monolinguals**	**Bilinguals**	**Trilinguals**
L2 AoA (years)		11.32 (7.82)	4.80 (5.39)
Years spoken L2		23.68 (16.19)	25.27 (15.21)
Proficiency in L1*	4.84 (.45)	4.42 (.85)	4.33 (1.11)
Proficiency in L2		4.29 (.78)	4.40 (.63)
PNT L1**	96.65 (2.80)	87.70 (14.17)	83.00 (18.82)
PNT L2		90.92 (9.98)	80.67 (15.54)
PNT L3			84.09 (13.48)
Use of L1 and L2***		36:64	
Use of L1, L2 and L3			22:26:56

*Self-reported, five-point scale (1 = very poor; 5 = very good), **Picture naming test accuracy (%), ***Daily percentage use

L2 AoA: Bilinguals acquired L2 significantly later than trilinguals ($p < .01$), but the number of years both groups had spoken their L2 did not differ ($p > .05$).

Balanced language skills: According to self-assessment there was no statistical difference between bilinguals or trilinguals' L1 and L2 proficiency (in both cases, $p >.05$). According to objective language proficiency assessment (PNT) there was no statistical difference between bilinguals' L1 and L2 proficiency, or trilinguals' L1, L2 and L3 (in all cases, $p >.05$). However, for L1 proficiency, monolinguals scored significantly higher than both bilinguals ($p < .02$) and trilinguals ($p < .01$). Bilinguals and trilinguals'

L1 objective proficiency did not statistically differ ($p > .05$), although bilinguals scored significantly higher than trilinguals on L2 ($p < .04$).

Daily language use: Bilinguals used L2 significantly more on a daily basis than L1 ($p < .01$). Trilinguals used L3 the most on a daily basis, which trend significantly differed from L1 ($p = .056$), but a statistical difference was not detected between L3 and L2, or between L1 and L2.

7.4.2 Analysis

For outliers the same criteria as in Colzato et al. (2008) and Hernández et al. (2010) were followed; responses faster than 100 ms or slower than 900 ms were excluded from the analysis (less than 3%). An alpha level of .05 was used in all statistical analyses.

To confirm that both facilitation and IOR effects were obtained in this sample, separate paired-samples t-tests were run between cued and uncued conditions at short SOA and long SOA respectively. RT at the short SOA was significantly faster to targets at the cued location than it was to uncued targets ($t(76) = -2.58$, $p < .02$), and at the long SOA RT was significantly slower to cued targets than uncued targets ($t(76) = 2.41$, $p < .02$). Thus, facilitation ($M = 16.07$ ms) was obtained at the short SOA and IOR ($M = -15.49$ ms) was obtained at the long SOA (Klein, 2000).

Global (monitoring), short cueing effect (facilitation) and long cueing effect (IOR) were submitted to a multivariate general linear model (GLM) as dependent variables, with language group (monolinguals, bilinguals, trilinguals) as a fixed factor. Because education marginally differed between monolinguals and bilinguals it was included as a covariate. Age was also included as a covariate for the same reason, as well as to explore any age effects. Similarly, an interaction term of language group x age was also included in the model to explore language group x age effects. This was repeated for the RT measures. The language group x age interaction was non-significant for both accuracy and reaction time measures and was therefore taken out of the model.

7.4.3 IOR accuracy

Mean accuracy of response per language group is shown in Table 6.

Table 6. Means and ±SEs (in parentheses) for the accuracy measures IOR global, and facilitation and IOR effects (%), by language group. Global is global accuracy of the task and facilitation and IOR effects are calculated as uncued minus cued

Language group	**Global ACC**	**Facilitation effect ACC**	**IOR effect ACC**
Monolinguals	97.30 (.90)	-.23 (1.33)	-.46 (1.60)
Bilinguals	97.95 (.87)	-.14 (1.29)	-.12 (1.55)
Trilinguals	95.26 (1.24)	.23 (1.84)	3.50 (2.21)

The multivariate GLM accuracy analysis revealed a significant main effect of age for IOR global ACC (F (1, 72) = 8.57, p = .005). However, the main effect of language group was non-significant.

To analyse the significant main effect of age further the data was submitted to a regression analysis, revealing that age significantly predicted IOR global ACC [β = -.08, SE = .03, (F (1, 75) = 9.32, p = .003), y axis intercept = 100.43 (SE = 1.20), with regression correlation coefficient r = -.33, p = .002] demonstrating a decreasing level of accuracy with increasing age.

7.4.4 IOR reaction time

Figure 11 shows a decline in global RT with increasing number of languages.

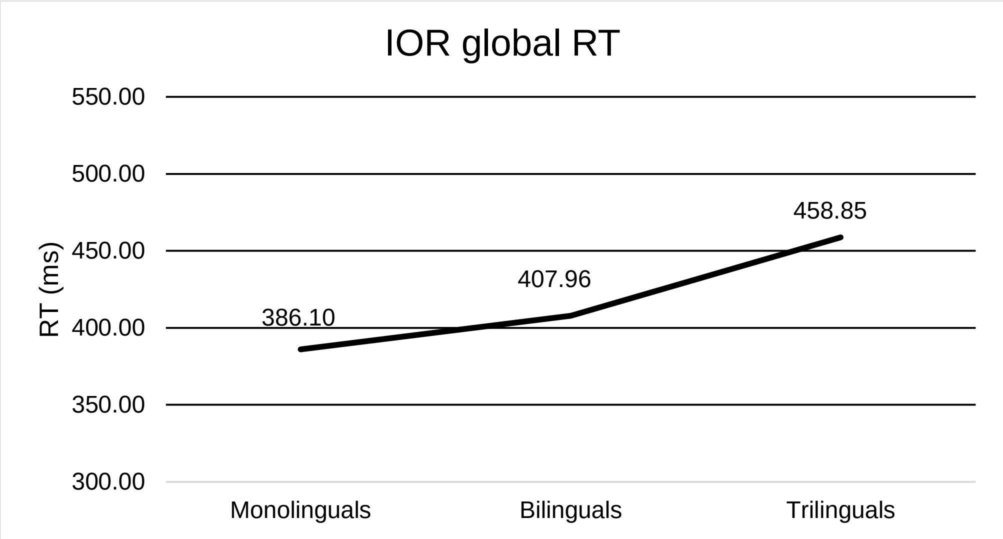

Figure 11. Means for global RT, as a function of language group. SEs: ML = ±14.49, BL = ±14.04 and TL = ±19.74.

Figure 12 shows the time course of the cueing effects facilitation and IOR.

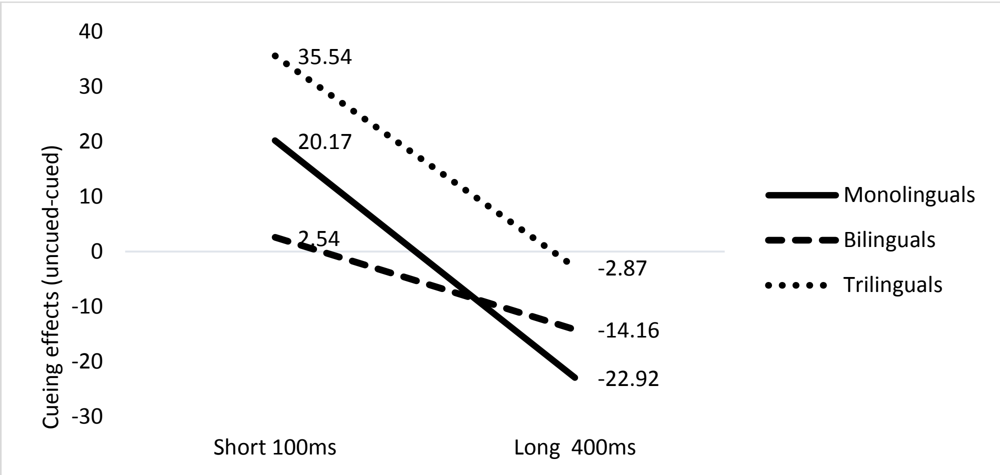

Figure 12. Time course of RT (ms) cueing effects at short (100 ms) and long (400 ms) SOAs. A positive score reflects facilitation (faster RTs) at the cued location, whereas a negative score reflects IOR (slower RTs) at the cued location. SEs for facilitation effect: [ML = ±10.20, BL = ±9.88, TL = ±14.10] and IOR effect: [ML = ±10.35, BL = ±10.35, TL = ±14.31].

The multivariate GLM reaction time analysis revealed significant main effects of age for global RT ($F (1, 72) = 44.08$, $p < .001$) and IOR effect RT ($F (1, 72) = 8.51$, $p = .005$), and a significant main effect of language group was present for global RT ($F (2, 72) = 4.29$, $p < .02$), but not for the IOR effect or the facilitation effect.

7.4.5 Main effect of language group

Univariate GLM was conducted to assess the main effect of language group on global RT, with pairwise comparisons revealing a significant overall trilingual disadvantage, compared to monolinguals ($p < .02$), but specific performance between monolinguals and bilinguals, and bilinguals and trilinguals did not differ. All language groups demonstrated facilitation at the short SOA and IOR at the long SOA.

7.4.6 Main effect of age

In order to further examine the main effects of age the data were submitted to regression analyses, revealing an increase in reaction time with older age, and that the magnitude of the IOR effect grew with increasing age [***global*** ($\beta = 2.69$, $SE = .44$, ($F (1, 75) = 36.91$, $p < .001$), y axis intercept = 304.23 ($SE = 19.46$), with regression correlation coefficient $r = .58$, $p < .001$) and ***IOR effect*** ($\beta = .82$, $SE = .31$, ($F (1, 75) = 7.14$, $p < .01$), y axis intercept = -44.36 ($SE = 13.56$), with regression correlation coefficient $r = .30$, $p = .005$)].

7.4.7 Summary of IOR data

There were no significant differences between the language groups in terms of accuracy of response. Global accuracy, however, decreased with increasing years of age. Age did not affect the accuracy of cueing effects.

Global RT increased with age, as did the magnitude of the IOR effect. However, facilitation RT was not affected by age. In terms of global RT trilinguals were outperformed by monolinguals, but no significant differences were detected between monolinguals and bilinguals, and bilinguals and trilinguals, respectively.

In terms of the cueing effects, all groups showed facilitation at short SOAs (albeit bilinguals a very small effect), and IOR at long SOAs (although trilinguals a very small effect), respectively, but no significant language group differences were detected.

7.5 Discussion

The aim of the current chapter was to further investigate the effect of trilingualism and age-related effects on the orienting network, which was measured by the IOR task. As far as I know this is the first time trilinguals' performance, compared to monolinguals and bilinguals', and ageing, has been measured by the IOR task. In the present investigation, the bilinguals and trilinguals had balanced language skills and were similar in regards to occupational status. Bilinguals had spent marginally significantly more years in education than monolinguals, but this was controlled for in the analyses. Monolinguals were significantly older than bilinguals and trilinguals, but age did not differ between bilinguals and trilinguals. Age was also controlled for in the analyses.

7.5.1 Main findings

A trilingual ***disadvantage*** was observed for IOR global RT, where trilinguals were outperformed by monolinguals. Although the means indicate worse performance with increasing number of languages, statistical differences were not observed between bilinguals and trilinguals, or between bilinguals and monolinguals. Importantly, both facilitation and

IOR effects were significant overall, and facilitation was seen at the short SOA and IOR at the long SOA. All language groups demonstrated facilitation at the short SOA and IOR at the long SOA. However the magnitudes of the cueing effects did not differ between the language groups, but the data suggest the language groups did not experience these at the same levels.

An age-related decline was present for global RT, and the magnitude of the IOR RT effect increased with age. However, age did not affect the facilitation RT effect. An age-related decline in accuracy of response (global) was also present, but age did not affect the cueing accuracy effects. The age-related decline observed on this task did not differ between the language groups.

7.5.2 Trilingualism and the orienting network

The finding that global RT (monitoring) did not differ between monolinguals and bilinguals fits well with findings by Colzato et al. (2008) and Hernández et al. (2010). Similarly, the finding that bilinguals and trilinguals' monitoring efficiency did not differ fits with the Chapter 5 finding of no between-group differences in global RT in the Simon task.

The observation that trilinguals were outperformed by monolinguals was however unexpected, and is not in line with the Chapter 5 finding of no between-group differences in monitoring in the Simon task. The mean age was significantly higher in monolinguals compared to trilinguals, although, this is unlikely to have influenced the result since a trilingual disadvantage, but not an advantage was observed. One possible explanation could be that the participants found the IOR task more challenging than the Simon task, as evident by slower RTs in the IOR task (Simon mean global RT = 314.59ms; IOR mean global RT = 417.64ms), which in turn may have resulted in a trilingual advantage. This would support the hypothesis that the more complex the task, the more likely it is to observe a bilingual advantage (e.g. Bialystok et al., 2014). Although note that an opposite pattern is observed here; a disadvantage of three languages as opposed to an advantage of two languages, compared to monolinguals. Furthermore, the efficiency of monitoring significantly decreased with age, which suggests that the difference between trilinguals and monolinguals is due to other factors than higher age in the monolingual group.

The observation that the cueing effects were not influenced by language group is in line with Hernández et al. (2010) and Costa et al. (2008). Nevertheless, as can be seen in Figure 12 in the results section of this chapter, the data indicate that the cueing effects exhibited some differences, similar to that seen in Colzato et. al. (2008), where monolinguals only showed facilitation at both 100ms and 400ms SOAs and bilinguals a very small IOR effect at 400ms.

7.5.3 Age effects

Age and bilingualism/trilingualism has not yet been explored in the IOR task, but the literature on ageing and IOR task performance shows mixed results in terms of the cueing effects. The present study provides new evidence regarding language group and age interaction in the IOR task, with the finding that no language group differences were detected in terms of age. This suggests that age-related performance on this task is not modulated by the number of languages people speak. That is, the age-related decline in orienting is not attenuated by monolingualism, bilingualism or trilingualism.

7.5.4 Methodological considerations

The present study only examined two SOAs (100 and 400 ms). The data suggest (although not significantly) that the language groups did not show the same magnitudes of the cueing facilitation at the short (100 ms) SOA and IOR at the long (400 ms) SOA, perhaps using a larger range in SOAs (for example, 100, 200, 300, 400, 500, 600 and 700 ms) would have shed more light on the impact of the three different language groups on the cueing effects. Future studies should consider this.

As noted in previous chapters, one of the implications of the findings in this study is that results of previous studies may be biased by the presence of trilinguals in a bilingual group.

7.6 Conclusion

The main aim of this chapter was to investigate the effect of trilingualism on the orienting network, as well as age effects. The data presented in this chapter indicate no benefit of speaking a third language on this network, and in fact, in some cases trilingualism may result in worse performance. This also suggests that if trilinguals are included in a “bilingual“ group for research purposes, it may confound the results. No between-group age-related differences were observed, suggesting that the number of languages one speaks does not modulate the normal decline with age. However, especially in the light that differences were not consistent in all conditions on the tasks, this study needs to be replicated (including more SOAs) in order to determine the effects of trilingualism and age on the orienting network.

7.7 Chapter summary of key points

- Previous studies, examining the bilingual advantage in young adults in the IOR task produced conflicting results.
- IOR has not yet been examined in trilinguals.
- Age effects have not yet been investigated in bilinguals/trilinguals in the IOR task.
- The present study investigated the effect of trilingualism on IOR task performance.

- Age was investigated on a continuum rather than comparing predetermined age groups.
- The language groups did not differ in terms of accuracy.
- A trilingual disadvantage was observed in global RT (monitoring).
- The means suggest a declining monitoring performance with increasing number of languages, but this pattern did not reach statistical significance.
- Data suggests that the language group differed in terms of the cueing effects, although this did not yield significance.
- Global accuracy declined with age, but the language groups did not differ in terms of the normal decline.
- Participants responded slower (global RT) and the IOR effect (RT) increased with increasing age.
- These findings may suggest that previous inconclusive findings on the bilingual advantage (Hernández et al., 2010; Costa et al., 2008) may have been confounded by trilingualism.
- Further research and replication with a larger sample, and a larger range in SOAs, is needed to confirm this disadvantageous effect of trilingualism in the IOR task.

Some of the information from this chapter can be found in Gudmundsdottir and Lesk (in preparation) ‘Trilingual Stroop and IOR performance’.

Chapter 8: Trilingualism and ageing on Stroop task performance

8.1 Introduction

Chapter 5 reported a trilingual disadvantage in inhibitory control but not in monitoring in the Simon task, whilst Chapter 7 reported a trilingual disadvantage (compared to monolinguals) in monitoring, but not in IOR. As mentioned in Chapter 7 the orienting network and cognitive control networks are thought to be independent (Fan et al., 2009, 2005, 2002), but do interact (Chen et al., 2010; Vivas et al., 2007; Raz, 2004; Vivas and Fuentes, 2001), and IOR has been found to interact both with the Stroop effect (Vivas and Fuentes, 2001) and the Simon effect (Wang et al., 2013; Ivanoff and Klein, 2002). The fact that a trilingual disadvantage was found on both the Simon task and the IOR task suggests a genuine disadvantage. However, performance on these tasks was not similarly affected by bilingualism, trilingualism and age. Unlike what was observed in the Simon task, the trilingual disadvantage seen in the IOR task was independent of age. This indicates that performance on these tasks is influenced by other factors. A reason for this could also be that trilingualism may only engage explicit inhibitory control (Simon effect) but not implicit inhibitory control (IOR effect), which further indicates that trilingualism may influence some components of cognitive control more than others.

To further investigate the effect of trilingualism on inhibition the present chapter compared monolinguals, bilinguals and trilinguals, and age, on a similar interference suppression task to the Simon task (Chapter 5); the Stroop task (Stroop, 1935). If inhibitory control measured by the Stroop task is similarly modulated by trilingualism as the Simon type inhibitory control, this suggests – as reported in Chapter 5 – that trilingualism modulates the cognitive control network (inhibitory control) using the Simon task, indicating that trilingualism modulates conscious rather than automatic inhibition mechanisms. The remainder of the introduction provides a short literature review of the Stroop paradigm, comparison of the Stroop and Simon paradigms, and the studies investigating the effect of bilingualism and age on this task.

8.1.1 Stroop task

The Stroop task (Stroop, 1935) has been widely studied since its development and is considered a reliable assessment tool in both clinical and research settings (Lezak et al., 2012). Including other aspects of EF, the Stroop task is believed to measure processing speed, sustained attention, response inhibition and cognitive flexibility (Barwick et al., 2012).

All variations of the Stroop task are based on the same fundamental paradigm: performance on a simple condition, where participants are, for example, required to read names of colours (congruent). Their score on this part is then compared with their performance on a second condition, where the participants are required to suppress a habitual response (incongruent); for example naming ink colours of fonts where the colour does not correspond to the semantic meaning of the colour word (e.g. ‘yellow’ printed in red ink, where the correct response is ‘red’). This creates a conflict between the word and colour stimuli where the dominant process determines the semantic meaning of the word, which then needs to be suppressed by means of a secondary process (naming of the ink colour) before a correct response can be made (Friedman and Miyake, 2004; Cohen et al., 1990). The increase in time taken to name the ink colours in the incongruent condition compared with the congruent condition is considered by many to be evidence of interference, often referred to as the Stroop effect (Van der Elst, 2006).

8.1.2 Stroop task versus Simon task

As a trilingual disadvantage was found in inhibitory control in the Simon task in Chapter 5, it will be interesting to see how trilingualism affects the

Stroop task. Both the Simon and Stroop paradigm are thought to measure inhibitory control (interference suppression). However, according to a neuroimaging study (Liu et al., 2004) they are thought to differ in terms of the source of the conflict which needs to be dealt with by inhibition. Liu and colleagues (2004) found unique activation patterns in the inferior parietal cortex for Stroop-type inhibition, which supports the assumption that in the Simon paradigm, the irrelevant information is spatial (in the traditional paradigm the location of the stimulus is on either left or right side of the screen), which leads to a stimulus-response conflict, whereas in the Stroop paradigm, the irrelevant information is a feature of the stimulus which leads to a stimulus-stimulus conflict (Liu et al., 2004).

A recent study by Blumenfeld and Marian, (2014) provided further evidence for this, and also that these two types of inhibition are differently affected by bilingualism. Blumenfeld and Marian (2014) compared performance on the Simon and Stroop tasks in young adult monolinguals and bilinguals. They investigated the hypothesis that bilingualism does not impact all inhibition mechanisms the same way. Blumenfeld and Marian (2014) reported a more enhanced Stroop task performance relative to the Simon task in bilinguals, but conversely monolinguals' performance on both tasks was more comparable. The authors suggested that resolving stimulus-stimulus type inhibition (Stroop task) rather than stimulus-response inhibition (Simon task) is more sensitive to the modulation of bilingualism. Perhaps it is not surprising that the bilingual advantage in young adults has been more consistently observed in the Stroop task than the Simon task (for an overview of studies, see Blumenfeld and Marian, 2014).

8.1.3 Stroop and ageing effects

Consistent with the normal age-related decrease in EF (Grady, 2012; Reuter-Lorenz and Park, 2010; Takio et al., 2009; Kray et al., 2004; Zelazo et al., 2004), the literature suggests that performance in the Stroop task declines with normal ageing, as evidenced by increased reaction time to both congruent and incongruent stimuli and a larger Stroop effect with age (Zurrón et al., 2014; Jackson et al., 2013; Peña-Casanova et al., 2009; Bugg et al., 2007; Mager et al., 2007; Van der Elst et al., 2006; MacLeod, 1991).

8.1.4 Bilingualism and Stroop task performance

As the present study employs a colour-word version of the Stroop task, this type of Stroop task will be focused on here. A bilingual advantage has been observed on other versions, such as a numerical (Hernández et al., 2010) and spatial arrow versions (Blumenfeld and Marian, 2014; Bialystok and dePape, 2009; Martin-Rhee and Bialystok, 2008).

8.1.4.1 Bilinguals and colour-word Stroop

Young adults

Using the electroencephalographic (EEG) method Coderre and van Heuven (2014) examined the proposed bilingual advantage in the Stroop task, with stimulus onset asynchrony (SOA) manipulation (see SOA definition in Chapter 7). They tested inhibitory control and monitoring. It was hypothesised by Costa et al. (2009) that an overall advantage on conflict resolution/inhibitory control tasks (i.e., greater monitoring) may suggest a more efficient monitoring system; a system that evaluates whether there exists a need to engage in conflict resolution processes. Hilchey and Klein's (2011) review later concluded that there was more evidence in the literature for a bilingual advantage in monitoring than inhibitory control.

Coderre and van Heuven's (2014) sample included young adults (mean age 22.8 years) divided into groups of 28 monolinguals and 25 bilinguals. The bilinguals reported learning their L2 before the age of 10 and being more dominant in their L1, and using it more often than their L2. However, they reported using both languages daily. The also reported slightly lower proficiency in L2 than in L1, although this was not statistically analysed. Sixteen bilinguals reported knowing other languages in addition to Mandarin and English, and six reported speaking a third language. Hence it remains unclear whether the bilingual group were truly bilingual. Bilinguals completed the Stroop task in both L1 and L2. Coderre and van Heuven (2014) did not find conclusive evidence for the enhanced inhibitory control in bilinguals, neither behaviourally nor in terms of EEG. As for monitoring, a bilingual advantage was reported in both L1 and L2. This was supported by EEG evidence, suggesting more efficient cognitive processing (monitoring) in bilinguals.

Young versus older adults

Bialystok et al. (2008) examined the bilingual advantage hypothesis in the Stroop task in young (mean age = 20 years) and older (mean age = 68 years) adults, divided into four groups of 24 participants in each. All participants completed the task in their L2. Many languages were involved, including Cantonese, French and Polish. All bilinguals reported using both languages daily, and in terms of self-rated speaking ability the bilinguals scored similarly in both their first (L1) and second (L2) language. Bilinguals were outperformed by monolinguals on the linguistic measures. Bialystok et al. (2008) reported that participants were quicker to read the colour words (congruent) than the colour ink (incongruent), and younger faster than older, although no language group differences were revealed in those trials. However, the researchers reported a larger Stroop effect (RT difference between congruent and incongruent trials) in older participants compared to younger. Although bilinguals completed the task in L2 and scored significantly lower than monolinguals on the linguistic measures, a significantly smaller interference was seen in bilinguals.

Kousaie and Phillips (2011) aimed to replicate Bialystok et al.'s (2008) findings, by comparing English monolinguals and English-French non-immigrant bilinguals. Both groups were divided into young and older adult groups with 38 young monolinguals and 35 young bilinguals (mean age = 23.1 years), and 25 older monolinguals and 20 older bilinguals (mean age = 70.4 years). All bilinguals reported using both languages on a daily basis and reported similar language proficiency in both languages as well as between the language groups, and an objective proficiency test showed a high relative L2 proficiency among bilinguals. Kousaie and Phillips (2011) reported an overall speed advantage on the task for young bilinguals compared to young monolinguals. They also reported a greater Stroop effect in older adults compared to younger adults; no bilingual advantage in inhibitory control was detected, however.

8.1.5 Stroop task and multilingualism

Limited evidence exists on the effect of trilingualism on performance in the Stroop task. Marian et al. (2013), however, looked at the effect of trilingualism and proficiency on inhibitory control on a colour-word task. They did, however, base their investigation on multilinguals' three most proficient languages, and thus the investigation was, more accurately, on multilinguals, but not pure trilinguals. Marian and colleagues (2013) reported that both accuracy and speed were significantly affected by multilinguals' language proficiency, whereby the Stroop task performance was most efficient in L1 and least efficient in L3. The means indicate a decreasing proficiency with from L1 to L3, but this was not statistically analysed. Further to this, the Stroop effect was observed in all three languages. They did, however, also report a more efficient performance in the within-language-competition condition than in the between-language-competition condition (the ink colour was named in a different language than the stimulus language).

8.1.6 Summary

A bilingual advantage has been observed on colour-word, numerical and spatial arrow versions of the Stroop task. Bialystok et al. (2008) who both tested young adults and older adults, whereby bilinguals completed the task in their L2, reported that younger participants responded overall faster than older participants, but a language-group difference was not observed in global RT. They further reported a greater Stroop effect in older adults, and a smaller Stroop effect in bilinguals. Kousaie and Phillips (2011) also tested younger and older participants, although their sample did not include immigrants. The bilinguals also completed the task in their L2. They reported an overall speed advantage for young bilinguals compared to young monolinguals, which does not fit Bialystok et al.'s (2008) findings. However, as in line with Bialystok et al. (2008) they observed a greater Stroop effect for older participants compared to younger participants, but unlike Bialystok et al. (2008) they did not observe a between-group difference on the Stroop effect.

As illustrated above, these three studies provide conflicting evidence regarding the bilingual advantage on the colour-word Stroop task. Bialystok et al. (2008) reported a bilingual inhibitory advantage but Kousaie and Phillips (2011) demonstrated a bilingual advantage in monitoring only, which is in line with the results of Coderre and van Heuven's (2014) investigation, in which both behavioural and EEG indications suggest more conclusive evidence of enhanced monitoring, rather than inhibitory control, in (young) bilinguals compared to monolinguals.

As far as I am aware, young and older monolinguals, bilinguals and trilinguals have not yet been compared in the Stroop task. Marian et al. (2013), however, looked at multilinguals' level of proficiency (in their three most proficient languages) and inhibitory control. They reported that both accuracy and speed were affected by language proficiency, where performance was statistically more efficient in L1 compared to L2 and L3, and in L2 compared to L3.

8.1.7 Trilinguals biasing bilinguals' results?

As previously mentioned in this thesis, some evidence suggests that bilinguals' performance on tests may be confounded by the presence of trilinguals in the bilingual group (see for example Chapter 5). A recent example in the Stroop/bilingualism literature is the study by Coderre and van Heuven (2014), who reported that 16 bilinguals knew other languages apart from their L1 and L2, and that six bilinguals also spoke a third language. Previous chapters of the present thesis strongly suggest that the presence of trilinguals may affect findings. In the case of Coderre and van Heuven (2014) the fact that they did not find consistent evidence for a bilingual advantage in inhibitory control may not necessarily mean that the bilinguals in the group did not show a superior performance compared to monolinguals. This may have been the finding simply because the trilinguals, or multilinguals in that group demonstrated a disadvantage, which balanced out the advantage among bilinguals.

8.2 Present study: research aims

The overall aim of this chapter is to examine the effects of trilingualism on inhibitory control, as measured by the Stroop word-colour task. This will shed light on whether the effect of trilingualism found in Chapters 5 and 7 is task-specific or a general one for tasks tapping into inhibitory control processes, as well as providing new evidence for the effect of trilingualism on the Stroop word-colour task. Due to the fact that the results from previous chapters, particularly from Chapters 5 and 7, do not match previous findings of a bilingual advantage it is difficult to predict the direction of the results here. However, due to Blumenfeld and Marian (2014) and Liu et al. (2004) it is expected that performance in the Stroop task will be more affected by bilingualism and trilingualism than was found in the Simon task in Chapter 5.

A second aim of the present chapter is to explore the effect of age. The present study examined age on a continuum rather than comparing groups of young and older adults. An age-related decline is expected in on all measures of the Stroop task, but based on previous studies (Kousaie and Phillips, 2011; Bialystok et al., 2008) language group differences in ageing were not expected.

8.3 Methods

The same participants [monolinguals (N = 31), bilinguals (N = 31) and trilinguals (N = 15)] as in chapter 7 completed the task in the current chapter. The same inclusion criteria, materials (lifestyle questionnaire and picture naming task) and same procedure as in chapter 7 were applied here.

Ethics approval was obtained from the Humanities, Social and Health Science Research Ethics Committee at the University of Bradford and all participants provided informed consent.

8.3.1 Stroop word-colour task

A standardised version of the Stroop task was used (Trenerry et al., 1989) which includes two tasks; colour task and word-colour task. Each task contains four columns of 112 colour names (blue, green, red, tan) written in an incongruent ink colour, but the order of the colour names in each task is different. In the first task (word reading) participants are given 30 seconds to read the colour words as quickly as possible. This is a measure of processing speed and will be referred to as "congruent" condition from now on. This task is followed by the second task (colour naming) where participants are given further 30 seconds to name the ink colour as quickly as possible, whilst ignoring the written colour name. This condition is a measure of interference and will be referred to as "incongruent" condition from now on. The task was administered in English.

8.3.2 Design

A quasi-experimental design was utilised, where the three language groups (monolinguals, bilinguals and trilinguals) were compared on the following measures:

(i) congruent, (ii) incongruent and (iii) the Stroop effect (congruent minus incongruent).

8.3.3 Procedure

The same procedure as in previous chapters was applied here (see Chapter 5 and 7).

8.4 Results

The aim of the current chapter was to compare monolinguals, bilinguals and trilinguals' performance, and age effects, on the Stroop word-colour task.

8.4.1 Characteristics and background measures

To recap, monolinguals' mean age (47.35 years) was significantly higher than for bilinguals (34.58 years) and trilinguals (30.93 years), but did not differ between bilinguals and trilinguals. There were no gender differences in terms of performance. Occupational status did not differ between groups, but bilinguals had spent marginally ($p = .059$) more years in education than monolinguals. Bilinguals acquired L2 significantly later than trilinguals ($p < .01$). According to self-report and objective assessment both bilinguals and trilinguals had balanced language skills. Bilinguals and trilinguals' L1 objective proficiency did not statistically differ ($p > .05$), although bilinguals scored significantly higher than trilinguals on L2 ($p < .04$). Bilinguals used

L2 significantly more on a daily basis than L1 ($p < .01$). Trilinguals used their L3 the most on a daily basis, which trend significantly differed from L1 ($p = .056$). See Chapter 7 for more details.

8.4.2 Analysis

The alpha level was set to .05 in all the analyses. In order to confirm that a Stroop effect was obtained in this sample a paired-samples t-test was run between the congruent and incongruent conditions. Participants named significantly more words in the congruent condition than the incongruent condition ($t(76) = 30.77$, $p <.001$), confirming an expected and significant Stroop effect ($M = 38.43$).

The congruent, incongruent and Stroop effect measures were submitted to a multivariate general linear model (GLM) as dependent variables, and language group (monolinguals, bilinguals, trilinguals) as a fixed factor. Age, education and score on the L1 PNT were submitted as covariates. An interaction term of language group x age was also included in the model to explore language group x age effects. However, the language group x age interaction was non-significant and was subsequently removed from the model.

Table 7 shows mean and standard error for the three measures under investigation by language group.

Table 7. Mean and ±SEs for congruent, incongruent and Stroop effect as a function of language group. The scores are mean numbers of words read in 30 seconds

Language group	Congruent	Incongruent	Stroop effect
Monolinguals	68.10 (2.25)	34.24 (.99)	33.87 (2.02)
Bilinguals	73.35 (2.12)	31.83 (.94)	41.53 (1.90)
Trilinguals	71.00 (3.09)	29.54 (1.37)	41.45 (2.78)

The multivariate GLM analysis revealed significant main effects of language group on the incongruent condition ($F(2, 71) = 3.56$, $p < .04$) and Stroop effect ($F(2, 71) = 3.86$, $p < .03$). Further to this, main effects of age were present for the congruent condition ($F(1, 71) = 4.68$, $p < .04$), the incongruent condition ($F(1, 71) = 63.95$, $p < .001$) and a trend toward significance for the Stroop effect ($p = .13$).

8.4.3 Main effects of language group

Separate univariate GLMs were conducted to assess the main effects of language group on the incongruent condition and the Stroop effect, with pairwise comparisons revealing that monolinguals outperformed trilinguals ($p = .03$) on the incongruent condition and the Stroop effect ($p < .04$). There was no significant difference, however, between bilinguals and trilinguals. As bilinguals' L2 picture naming task (PNT) score was significantly higher than the L2 PNT score of trilinguals, the groups were compared on the Stroop measures following the same method of analysis as above, with L2 PNT as a covariate. The analysis still revealed comparable performance on all measures for both language groups.

8.4.4 Main effects of age

Regression analyses revealed that age significantly predicted both ***congruent condition*** [β = 77.49, SE = 2.83, (F (1, 75) = 7.17, p < .01), y axis intercept = -.17 (SE = .06), with regression correlation coefficient r = -.30, p = .005] and the ***incongruent condition*** [β = 39.82, SE = 1.40, (F (1, 75) = 36.23, p < .001), y axis intercept = -.19 (SE = .03), with regression correlation coefficient r = -.57, p < .001] revealing a linear decrease in performance with older age.

8.4.5 Summary of Stroop data

Bilinguals and trilinguals' performance on all three measures did not statistically differ, neither did that of monolinguals and bilinguals. However, trilinguals were outperformed by monolinguals on the incongruent condition and the Stroop effect, but the groups showed similar performance in the congruent condition. An age-related decline was seen for all participants on the congruent and incongruent condition. A trend was also seen on the Stroop effect. There was no significant interaction between language group and age.

8.5 Discussion

The aim of the present chapter was to further investigate the effect of trilingualism and age-related effects on inhibitory control. To the author's knowledge, age x trilingualism interaction has not yet been explored on the Stroop word-colour task. As a reminder, the bilinguals and trilinguals had balanced language skills.

8.5.1 Main findings

All groups performed comparably on the congruent condition (processing speed). Monolinguals outperformed trilinguals, but not bilinguals on the incongruent condition and Stroop effect. Bilinguals and trilinguals' scores did not significantly differ on any of the conditions.

An age-related decline was present for congruent and incongruent conditions, but the Stroop effect remained stable with age, although there was a marginal effect of age ($p = .13$). As expected, the three language groups did not differ in terms of age.

8.5.2 The effect of trilingualism on the Stroop colour-word task

The finding that bilinguals and trilinguals did not differ on any of the conditions of the Stroop task suggests that compared to bilinguals, trilinguals do not experience enhanced or diminished inhibitory control or processing speed.

The finding that in the present sample the monolinguals were found to outperform trilinguals on the incongruent condition and on the Stroop effect, is not in line with Bialystok et al. (2008), who found a bilingual advantage on the Stroop effect. However the fact that no between-group differences were discovered on the congruent condition is in line with Bialystok et al. (2008), but contradicts the results of Kousaie and Phillips (2011).

8.5.3 Age effects

The age-related decline in the Stroop task is in line with the literature (Zurrón et al., 2014; Peña-Casanova et al., 2009; Van der Elst et al., 2006; Mager et al., 2007; MacLeod, 1991) as well as with the findings of Kousaie and Phillips (2012) and Bialystok et al. (2008). However, the result that the magnitude of the Stroop effect remained stable with age is unexpected and contradicts previous studies, including that of Kousaie and Phillips (2011) and Bialystok et al. (2008). The finding that a language group and age interaction did not reveal significance on any of the Stroop task measures is consistent with Kousaie and Phillips (2011) and Bialystok et al. (2008).

8.5.4 Comparison of Simon task (Chapter 5), IOR task (Chapter 7) and Stroop task (present chapter)

Thus far, three types of inhibitory control measures have been examined in this thesis. Although trilingualism modulated performance on all of these tasks, the effects were not consistent across the tasks. However, as Table 8 indicates, trilingualism modulates Simon type and Stroop type inhibition but not IOR type inhibition.

Table 8. Overview of the effects of trilingualism (TL) on the three inhibition tasks; Simon task, Stroop task and IOR task

Measures	Simon task	Stroop task	IOR task
Inhibitory control	TL disadvantage with increasing age	TL disadvantage	X
Monitoring/ Processing speed	X	X	TL disadvantage

8.5.5 Implications

Coderre and van Heuven (2014) did not discover consistent evidence for a bilingual advantage in inhibitory control. As mentioned in the introduction, their "bilingual" cohort included trilinguals/multilinguals. The finding of a trilingual disadvantage in the present chapter may suggest that the inconsistent finding of a bilingual advantage on the Stroop effect by Coderre and van Heuven (2014) is simply due to the fact that trilingualism/multilingualism biased the results.

8.6 Conclusion

The main aim of this chapter was to investigate the effect of trilingualism on inhibitory control. The data presented here indicates no benefit of speaking a third language on Stroop-type inhibition mechanisms and in some cases trilingualism may result in worse performance. This may suggest that if trilinguals are included in a bilingual group it may confound the results. No between-groups differences were found in terms of ageing, suggesting that the number of languages one speaks does not modulate the normal decline in age on this particular inhibition task. However, especially in the light that differences were not consistent in all conditions, this study needs to be replicated in order to determine the effects of trilingualism and age on Stroop-type inhibition.

8.7 Chapter summary of key points

- A bilingual advantage has been reported on colour-word, numerical and spatial arrow versions of the Stroop task.
- The evidence on the effects of bilingualism on the Stroop colour-word task is inconsistent.
- Coderre and van Heuven (2014) who did not find conclusive evidence of a bilingual advantage in inhibitory control included trilinguals/multilinguals in the “bilingual” cohort, which may have confounded this result.
- Exploring the effect of trilingualism is particularly important as some studies, such as Coderre and van Heuven (2014), do not have a pure bilingual group.
- Young and older monolinguals, bilinguals and trilinguals have not yet been compared in the Stroop task, looking at age on a continuum (as far as I know).
- All groups performed similarly on the congruent condition, which is consistent with similar monitoring performance among the language groups in the Simon task (Chapter 5), but not in the IOR task (Chapter 7).

- A trilingual disadvantage was observed in inhibitory control, which is consistent with the Simon task, but not the IOR task.
- In line with Kousaie and Phillips (2011) and Bialystok et al. (2008) the age-related decline in the Stroop task was not modulated by language group.
- The data presented here indicates that trilingualism may bias bilinguals' performance.

Some of the information from this chapter can be found in Gudmundsdottir and Lesk (in preparation) 'Trilingual Stroop and IOR performance'.

Chapter 9: The level of task complexity and trilingualism

9.1 Introduction

Chapters 5 and 6 tested the hypothesis that the experience of managing three languages, rather than two or one, may result in greater enhancement of inhibitory control, monitoring and WM (WM). The results demonstrated a trilingual disadvantage (compared to monolinguals and bilinguals) in inhibitory control, after the age of around 29 years, and no statistical difference between the language groups in monitoring. Additionally, a bilingual and a trilingual disadvantage in WM, but age was not modulated by language group in the N-back task.

Previous research has provided evidence that a bilingual advantage may only become apparent in young adults when the cognitive tasks are complex (Bialystok et al., 2014; Morales et al., 2013; Bialystok, 2006, for a review see Bialystok et al., 2012), which has been attributed to young adults being *"at the developmentally peak age for cognitive control"* (Bialystok et al., 2012:6). Given this literature, then, in order to thoroughly investigate any effect of trilingualism on cognition, task difficulty must be studied. The present chapter therefore examines monolinguals, bilinguals and trilinguals' performance in the Simon task and N-back task, where complexity is manipulated.

The main aims are thus to examine whether the between group differences will become more pronounced with increasing level of complexity, as well as any age-related differences, central to this thesis. The remainder of this section will introduce the complexity literature.

9.1.1 Bilingualism and level of complexity

The evidence regarding the impact of the level of complexity on cognitive control and WM tasks still remains elusive, and for trilinguals it is nonexistent. The existing evidence for monolinguals and bilinguals' performance under simple and complex conditions measuring cognitive control is limited, and inconsistent. The remaining sub-sections will introduce the current evidence, both in terms of WM and cognitive control.

9.1.1.1 Inhibitory control/monitoring

At least two studies have examined bilingualism, the level of complexity, and age, using the Simon task. Bialystok et al. (2004, experiment 2) investigated a simple versus complex Simon task performance in young (mean age = around 43 years) and older (mean age = around 70 years) monolingual and bilingual adults. Accuracy of response was similar under both the simple and the complex conditions of the Simon task, and a higher accuracy for older participants compared to younger was observed, but no language group differences were seen. Younger participants responded faster (better monitoring) than older participants, and bilinguals faster than monolinguals in both the simple and the complex task. A more pronounced increase with age in RTs for monolinguals than bilinguals was reported, but only on the complex task. They further reported larger WM costs (difference in RTs between simple and complex tasks) with age, but the costs were smaller in bilinguals compared to monolinguals. Regarding inhibitory control, an age-related increase in the Simon effect was observed, which was more pronounced in the complex task, and was less for bilinguals. Salvatierra and Rosselli (2010), who only examined performance in inhibitory control, investigated performance of young (mean age = around 26 years) and older (mean age = around 64 years) adult monolinguals and bilinguals on simple and complex Simon tasks. They only looked at the Simon effect, not monitoring (global RT). They reported that older bilinguals outperformed older monolinguals, but only on the simple task. There was no difference between the younger language groups.

9.1.1.2 WM

As mentioned previously, the level of complexity of WM tasks and bilingualism has received little attention thus far, and as far as I am aware no study has investigated the level of complexity of WM tasks in the bilingual (or trilingual) literature. A recent study by Ratiu and Azuma (2014) compared young adult monolinguals and bilinguals on what they considered complex, verbal, and non-verbal WM tasks (standard operation span task, backward digit span task and non-verbal symmetry span task). Although the authors expected a bilingual advantage on all tasks, they thought it was most likely to emerge on the non-verbal task, given previous literature on bilingual disadvantage on verbal tasks. Both groups demonstrated similar performance on all WM tasks, including the non-verbal task. Although this indicates that monolinguals and bilinguals show similar performance as measured by complex WM tasks, comparison with less complex tasks is lacking.

9.1.1.3 Inhibitory control/monitoring and WM

Thus far, two studies have examined WM, cognitive control, and ageing together. Bialystok et al. (2008) compared younger and older monolinguals and bilinguals on relatively simple WM tasks (forward and backward Corsi blocks (visuospatial WM) and the self-ordered pointing task (non-spatial executive WM)). To tap into cognitive control, the language groups were also compared on simple tasks (the Simon arrow task and the Stroop colour-naming task). WM performance was similar, but a bilingual advantage was observed on the Simon and Stroop tasks, where the difference was larger in the older age group.

More recently, Bialystok et al. (2014, study 2) investigated whether bilinguals would show an advantage on a complex WM task (the recent probe task) in younger (mean age = around 21 years) and older monolinguals and bilinguals (mean age = around 71 years). The participants completed a verbal and non-verbal condition. Young participants were faster and more accurate under both conditions. A bilingual advantage was observed in the non-verbal condition of the task (not verbal condition). The authors also reported that this bilingual advantage was more prominent in the older age group. Bialystok et al. (2014 – study 1) also examined cognitive control, although a simple task was employed (the Stroop task). Older bilinguals responded faster than older monolinguals on the interference condition, and bilinguals outperformed monolinguals in terms of interference, in both age groups.

Although Bialystok and colleagues (2014, 2008) did not manipulate the level of complexity, their findings suggest that the bilingual advantage emerges under more demanding WM loads, as seen by similar between group performance on the relatively simple WM tasks (Bialystok et al., 2008) and a bilingual advantage on a more complex non-verbal task (Bialystok et al., 2014). Furthermore, the difference between monolinguals and bilinguals in WM performance was larger for older adults than younger adults. In line with many previous studies, a bilingual advantage was seen in cognitive control on simple tasks (Simon and Stroop tasks) and this difference was larger for older adults (Bialystok et al., 2014, 2008). These results are, however, not informative regarding complexity, but do show that even though bilinguals outperformed monolinguals on a simple cognitive control task, both groups showed similar WM capacity (Bialystok et al., 2008), which indicates that these two constructs are separate but not related, as suggested by Miyake and Friedman (2012)

9.1.1.4 Summary

The available evidence regarding the level of complexity of WM and cognitive control tasks is partial. Regarding WM, similar performance between monolinguals and bilinguals was reported on simple WM tasks (Bialystok et al., 2008). The evidence from complex tasks is not in agreement; similar performance has been reported on complex span tasks (Ratiu and Azuma, 2014), but a bilingual advantage has been reported on the non-verbal condition of the recent probe task (Bialystok et al., 2014). The level of complexity within a task was not manipulated in either study, although the recent probe task is considered more difficult than the span tasks (Bialystok et al., 2014). Taking this into consideration, the latter finding (Bialystok et al., 2014) indicates that under more demanding (than span tasks) WM conditions bilinguals do demonstrate an advantage, compared to monolinguals. The level of complexity has been manipulated in two studies (Bialystok et al., 2004 and Salvatierra and Rosselli, 2010) investigating cognitive control. Both studies employed the Simon task, but reported mixed results. Bialystok et al. (2004) reported a bilingual advantage under both the simple and complex conditions, but Salvatierra and Rosselli (2010) only under the simple condition.

9.1.2 N-back and complexity

Using memory span tasks and the recent probe task to investigate WM capacity in different language groups has its advantages. For example, the complex span task is thought to reflect the executive attention aspects of WM (Kane et al., 2007), and is considered to be a reliable measure of WM (Redick et al., 2012), although, importantly, it is not thought to involve updating (Wilhem et al., 2013). The recent probe task was used by Bialystok et al. (2014) as a measure of monolinguals and bilinguals' ability to resolve interference in WM. Although arguably more complex than the span tasks, this type of task is thought to be relatively simple compared to the N-back task, as cognitive control mechanisms are not as heavily taxed (Jonides and Nee, 2006). Referring back to the updating (also, inhibition and shifting) factor in the previously mentioned (see for instance Chapter 3) model of Miyake and colleagues (Miyake and Friedman, 2012; Friedman et al., 2008; Miayke et al., 2000), which is often used by researchers in this area to explain the underpinnings of the bilingual advantage in EF, and WM – it can be argued that the N-back task is a more appropriate tool to probe the updating component than the span tasks and recent probe task. This is due to the fact that the N-back task is known for the requirement to continuously update memory to store the last stimuli (for example numbers) of a sequence, and to evaluate each stimulus presented as to whether it matches another stimulus presented earlier in the sequence. Also, this task is arguably better suited to investigate the link between the level of complexity and bilingualism and, as in the case of the present study, trilingualism, as it can go from a very simple reaction time level (zero-back) to much higher load levels. As with the span tasks, the N-back task is considered a reliable measure of WM (Unsworth et al., 2010; Jaeggi et al., 2010; Krumm et al., 2009; Unsworth, 2010; Schmiedek et al., 2009a).

9.2 Present study: research aims

The complexity literature regarding bilingualism, inhibition, monitoring and WM is scarce, and has not yet produced conclusive evidence. Not many studies have compared monolinguals and bilinguals under simple and complex conditions of the Simon task, and as far as I am aware, none have examined this in young to middle-aged adults, comparing monolinguals, bilinguals and trilinguals. Regarding WM and complexity, most studies have examined children, although more recently the attention has been directed towards older age groups. As with the Simon task, as far as I know, this has not been investigated in this age range, on a numerical N-back task, in monolinguals, bilinguals and trilinguals, on four levels of complexity. However, given that there are at least some interesting findings in the literature, it is important to follow this up on the studies of this thesis. As mentioned above, the present chapter further examined performance of monolinguals, bilinguals and trilinguals in the Simon task and the N-back task, by adding more and less complex levels to the tasks.

Based on the results from Chapters 5 and 6, it was hypothesised that performance on both the Simon task and N-back task would be modulated by bilinguals and trilinguals, where disadvantages in these groups compared to monolinguals would be observed.

It was also hypothesised that bilinguals and trilinguals would show a comparable performance.

It was further hypothesised that the differences between trilinguals and monolinguals, and bilinguals and monolinguals, would increase with increasing level of complexity (on both tasks).

It was hypothesised that an age-related decline would be observed on both tasks.

Lastly, it was hypothesised that the expected language group differences would increase with increasing age, and level of complexity.

9.3 Methods

9.3.1 Participants

Sixty five participants (54 females and 11 males), ranging in age from 19 to 55 years (M = 25.82, SD = ±9.04) participated in the experiment, and were divided into three groups of monolinguals (N = 17), bilinguals (N = 29) and trilinguals (N = 19). The same inclusion criteria as in Chapter 5 was applied here. Ethics approval was obtained from the Humanities, Social and Health Science Research Ethics Committee at the University of Bradford and all participants provided informed consent.

<u>Monolinguals</u>

All monolinguals had English as their first language and were not functionally fluent (able to hold a conversation) in any other language but English.

Bilinguals

The bilinguals had various languages as their first language, and three had English as their first language. Most bilinguals had English as their second language. The non-English languages were Punjabi (N = 5), Greek (N = 4), English (N = 3), Polish (N = 3), Urdu (N = 3), Estonian (N = 2), Yoruba (N = 2), and German, Gujarati, Hindi, Hungarian, Maltese, Pashto and Turkish (N = 1 each).

Trilinguals

Trilinguals had various languages as a first language [Punjabi (N = 4), English (N = 3), German (N = 2), Gujarati (N = 2), Kurdish (N = 2), Arabic, Bulgarian, Hinko, Kirundi, Spanish and Urdu (N = 1 each)], a second language [English (N = 8), French (N = 3), Urdu (N = 3), Arabic, Danish, Potwari, Swedish, and Spanish (N = 1 each)] and a third language [English (N = 8), Urdu (N = 6), Punjabi (N = 3), Arabic (N = 1) and Russian (N = 1)].

9.3.2 Materials

9.3.2.1 Lifestyle questionnaire

An updated version of the lifestyle questionnaire applied in previous chapters (5-8) was administered (see Appendix 2). The language experience part of the questionnaire was adapted from Marian et al. (2007). The questionnaire included the same demographic, lifestyle and language background information, but the scale of self-reported proficiency changed from a five to ten answer option (1 = very poor, 10 = very good), where participants separately rated their writing skills, reading skills, speaking skills and understanding spoken language, which were then converted into a composite score of proficiency for each language. Due to evidence suggesting that bilinguals and monolinguals' SES may confound their performance (see Hilchey and Klein, 2011; Morton and Harper, 2007), several measures of SES were also added to the questionnaire (participant's educational level, parents' educational level and occupational status, and social class). Noteworthy is that in a study published after the start of this experiment, an association was not observed between cognitive control and SES, in older monolinguals and bilinguals (Kirk et al., 2014).

9.3.2.2 The Simon task

The same task as was used in Chapter 5 was administered, with an added condition; a complex condition (Bialystok et al., 2004), where four coloured squares (pink, brown, green, yellow) appeared on either left or right side of the screen. Participants were instructed to press the left key when they saw a pink or brown square, and the right key if they saw the green or yellow square. As in Bialystok et al. (2004) the instructions were given as four individual rules. This was done to associate each colour with the correct response key. This condition is thought to place greater demands on WM than the simple condition. Four practice trials preceded the simple condition and eight preceded the complex condition. See Chapter 5 for a more detailed description of the task.

9.3.2.3 N-back

The same version of the N-back task that was used in Chapter 6 was administered; however, the present task consisted of four conditions: 0-back, 1-back, 2-back and 3-back. 0-back is a control condition, in which participants were required to indicate whether a number matched a pre-specified number (0). This requires sustained attention but involves no WM demand. In the 1-back condition, each number was compared with the previously presented number to determine whether it was the same number or not. In the 2-back condition, each number was compared with the number presented two numbers back. In the 3-back condition, which has the highest memory load, each number was compared with the number presented three numbers back. Thus, with increased numbers to remember WM demand increases. See Chapter 6 for a more detailed description of the task.

9.3.2.4 Non-verbal reasoning

To control for fluid intelligence (particularly important when updating demands are high (Friedman et al., 2006)), a short, non-verbal reasoning (abstract reasoning) test was applied where participants were given 12 minutes to solve 20 questions. This test is similar to Raven's Matrices (Raven, 1936), which tests non-verbal abstract reasoning (fluid general intelligence).

9.3.3 Procedure

The sessions took place in the Psychology Laboratories in the Division of Psychology at the University of Bradford. On arrival, participants were allocated individual cubicle rooms where consent was obtained. The testing session then commenced, whereby participants completed the tests and the lifestyle questionnaire in the same order.

9.4 Results

The main aim of the present chapter was to examine whether the trilingual and bilingual disadvantages seen in Chapters 5 and 6 would remain, and whether they would become more pronounced as the level of complexity of the tasks increased. Potential age-related differences were also examined.

9.4.1 Characteristics and background measures

Age did not differ between the language groups, and there were no gender differences in terms of performance. On average, participants had spent 16.85 years in education (SD = ±2.73), which did not differ between the language groups. Further to this, participants reported their highest level of education, their parents' highest level of education and current (or last) occupational level, as well as social class, all of which did not differ between the language groups (see Table 9).

Table 9. Means and ±SDs of background characteristics, by language group

	Monolinguals		**Bilinguals**		**Trilinguals**	
	Mean	±SD	Mean	±SD	Mean	±SD
Age	28.47	9.82	24.38	8.66	25.63	8.84
Years of education	16.65	3.35	16.38	2.05	17.74	2.96
Highest level of education*	4.88	1.27	4.28	.70	4.89	1.49
Mother's highest level of education	2.53	1.55	2.76	1.72	3.05	2.27
Father's highest level of education	2.35	1.06	3.21	1.99	3.68	2.43
Mother's occupational level**	3.41	1.12	2.72	1.62	2.58	1.68
Father's occupational level	3.53	1.07	3.31	1.14	3.68	1.34
Social class***	3.06	.90	2.97	.73	2.68	.89

*= Scale 1 to 8 (1 = less than high school, 8 = earned a PhD/MD), **= Scale 1 to 5 (1 = professional/managerial, 5 = unemployed, ***= Scale 1 to 4 (1 = high middle class, 4 = working class).

The mean age of L2 AoA among bilinguals was 7.64 years (SD = ±7.49) and 3.72 years (SD = ±2.82) among trilinguals. Mean age of L3 among trilinguals was 9.00 (SD = ±4.17). Bilinguals used their L2 significantly more on a daily basis (mean daily language use: L1 = 39%, L2 = 61%), $t(27) = -2.63$, $p < .02$. Trilinguals' mean daily language use (L1 = 25%, L2 = 42%, L3 = 33%) did not statistically differ.

Bilinguals had balanced proficiency in both of their languages [L1: $M = 8.55$, $SD = \pm1.92$; L2: $M = 8.23$, $SD = \pm1.73$, $p > .1$], as did trilinguals for all of their languages [L1: $M = 8.55$, $SD = \pm1.67$; L2: $M = 8.80$, $SD = \pm1.29$; L3: $M = 7.99$, $SD = \pm1.61$, L1 vs. L2 and L1 vs L3: $p > .1$; L2 vs L3: $p = .063$].

GLM analysis revealed a significant main effect of language group on the non-verbal reasoning task (monolinguals: $M = 10.47$, $SD = \pm3.14$; bilinguals: $M = 8.97$, $SD = \pm3.34$; trilinguals: $M = 7.91$, $SD = \pm1.77$), $F(2, 62) = 4.91$, $p = .01$, with pairwise comparisons revealing a trilingual disadvantage in performance compared to monolinguals ($p < .01$), but no difference between monolinguals and bilinguals, and bilinguals and trilinguals.

9.4.2 Simon task

9.4.2.1 Analysis

Mean accuracy scores and mean response latencies (RTs) were calculated for each participant. Outliers more than two SDs from the mean were excluded from the analysis (less than 5%).

The data were submitted to a multivariate GLM, with easy Simon effect RT, easy global RT, complex Simon effect RT, complex global RT, easy global accuracy (%) and complex global accuracy (%) as dependent variables, language group (monolinguals, bilinguals, trilinguals) as a fixed factor, and non-verbal reasoning and as covariates.

9.4.2.2 Complexity

Table 10 shows group means and standard errors under both easy and complex conditions of the Simon task.

Table 10. Mean reaction time scores (ms), mean accuracy scores (%) and ±SEs (in parentheses) for easy (E) and complex (C) versions of the Simon task, by language group

	Monolinguals	**Bilinguals**	**Trilinguals**
E-Simon effect RT	54.24 (8.83)	57.78 (6.51)	37.51 (8.35)
C-Simon effect RT	34.74 (7.65)	38.21 (5.64)	26.54 (7.24)
E- global RT	250.16 (15.85)	292.64 (11.69)	265.85 (15.00)
C- global RT	330.25 (17.15)	356.50 (12.65)	351.94 (16.23)
E-global ACC (%)	93.41 (1.31)	91.00 (.97)	92.95 (1.24)
C-global ACC (%)	93.55 (1.60)	88.54 (1.18)	92.40 (1.52)

After controlling for non-verbal reasoning, the multivariate GLM analysis revealed a significant main effect of language group on complex global (ACC), $F(2,61) = 3.98$, $p < .03$, and a trend for easy global (RT), $p = .081$). The means for the trend indicate a bilingual disadvantage (compared to monolinguals and trilinguals). In order to investigate the significant main effect, complex global ACC was submitted to a univariate analysis of covariance (ANCOVA), which confirmed the significant main effect, and pairwise comparisons revealed that accuracy of response was lower for bilinguals compared to monolinguals ($p < .05$). There were no other significant main effects.

9.4.2.3 Age effects

There were significant main effects of age for both easy global ACC, F (1, 60) = 8.98, p = .004) and complex global ACC, (F (1, 60) = 8.41, p = .005). Regression analyses revealed that age significantly predicted both measures [***easy global ACC***: β = 87.03, F (1, 63) = 8.37, p = .005, y axis intercept = .20 with regression correlation coefficient r = .34, p = .003; ***complex global ACC***: β = 83.91, F (1, 63) = 10.25, p = .002, y axis intercept = .27 with regression correlation coefficient r = .37, p = .001], where the level of accuracy of response increased with increasing age.

9.4.3 Summary of Simon, complexity and age

The analysis of the Simon task showed that no statistical differences were detected between the language groups in terms of RTs, under either simple or complex conditions. ACC was not modulated by language group under the simple condition, but under the complex condition a bilingual disadvantage (compared to monolinguals) was observed. Thus, bilinguals and trilinguals' performance did not statistically differ. Lastly, age only predicted the ACC measures, whereby accuracy of response improved with age.

9.4.4 N-back task

9.4.4.1 Analysis

RTs more than two standard deviations from the mean were removed for each participant (less than 5%). RTs and ACC for successful matches and non-matches were only used in the analysis.

The following N-back reaction time (RT) and accuracy (ACC) measures were investigated (both match and non-match trials); (i) 0-back, (ii) 1-back, (iii) 2-back, (iv) 3-back, (v) 1 minus 0 (N-back) effect, (vi) 2 minus 0 (N-back) effect, and (vii) 3 minus 0 (N-back) effect. To clarify, it should be noted that the N-back effects are thought to reflect increasing load on WM.

The aforementioned variables were submitted to a multivariate GLM as dependent variables, with language group (monolinguals, bilinguals, trilinguals) as a fixed factor, and non-verbal reasoning and age as covariates. Accuracy and reaction time measures were analysed separately.

9.4.4.2 Complexity

Tables 11 to 14, which can be found in Appendix 3, show the mean accuracy of response (%) and RTs (ms) of both match and non-match trials in 0-back to 3-back conditions, and RT and ACC N-back effects for both match and non-match trials.

After controlling for non-verbal reasoning, the multivariate GLM analysis (for the ACC measures) revealed trends for 0-back match ACC ($p = .089$), 3-back match ACC ($p = .1$), 3-back non-match ACC ($p = .066$), 0 minus 3 (match) effect ($p = .063$) and 0 minus 3 (non-match) effect ($p = .092$). The means for these trends indicate a trilingual advantage (compared to monolinguals and bilinguals) on 0-back match ACC, a bilingual disadvantage (compared to monolinguals, and trilinguals between) on the 3-back measures, and 0 minus 3 effects.

For the RT measures, the multivariate GLM analysis revealed trends for 3-back match RT ($p = .1$) and 3 minus 0 (match) effect RT ($p = 0.87$), with means indicating slower RT with increasing languages on 3-back match RT and a trilingual disadvantage (compared to monolinguals and bilinguals) on the 3 minus 0 (match) effect RT.

9.4.4.3 Age effects

Accuracy

In terms of accuracy, a significant main effect of age was observed on 0-back match (F (1, 58) = 812, p <.01), 0-back non-match (F (1, 58) = 4.54, p < .04), 1-back match (F (1, 58) = 8.67, p < .01), 1-back non-match (F (1, 58) = 4.86, p < .04). Trend effect of age was seen for 0 minus 1 (match) effect (p = .063).

Regression analyses revealed that age significantly predicted ***0-back match ACC*** [β = 91.82, F (1,61) = 4.12, p < .05, y axis intercept = .14 with regression correlation coefficient r = .25, p < .03; ***0-back non-match ACC***: [β = 96.61, F (1,61) = 5.56, p < .03, y axis intercept = .07 with regression correlation coefficient r = .29, p < .02], ***1-back match ACC*** [β = 74.11, F (1,61) = 7.51, p < .01, y axis intercept = .45 with regression correlation coefficient r = .33, p < .01] ***1-back non-match ACC*** [β = 91.29, F (1,61) = 3.98, p = .05, y axis intercept = .19 with regression correlation coefficient r = .25, p < .03], where accuracy of response improved with older age.

Reaction time

In terms of reaction time, a significant main effect of age was observed for 3-back match RT (F (1, 58) = 5.83, p < .02), 3-back non-match RT (F (1, 58) = 5.74, p = .02), 3 minus 0 (match) effect (F (1, 58) = 5.88, p = .02), 2 minus 0 (non-match) effect (F (1, 58) = 5.05, p <.03) and 3 minus 0 (non-match) effect (F (1, 58) = 6.33, p < .02. Trend was seen for 2-back non-match RT (p = .056).

Regression analyses revealed that age significantly predicted ***3-back match RT*** [β = 574.60, F (1,61) = 4.30, p < .05, y axis intercept = 6.27 with regression correlation coefficient r = .26, p < .03], ***3-back non-match RT*** [β = 546.40, F (1,61) = 4.34, p < .05, y axis intercept = 7.88 with regression correlation coefficient r = .26, p < .03], ***2 minus 0 (non-match) effect RT*** [β = 49.40, F (1,61) = 6.74, p < .02, y axis intercept = 6.55 with regression correlation coefficient r = .32, p < .01], ***3 minus 0 (match) effect RT*** [β = 134.48, F (1,61) = 3.99, p = .05, y axis intercept = 5.73 with regression correlation coefficient r = .25, p < .03] and ***3 minus 0 (non-match) effect RT*** [β = 100.97, F (1,61) = 4.30, p < .05, y axis intercept = 7.72 with regression correlation coefficient r = .26, p < .03], whereby and age-related decline was observed (increased RTs and larger N-back effects with older age).

9.4.5. Summary of N-back, complexity and age

In the N-back task, several trends were observed, both in terms of ACC and RTs, with the means suggesting worse performance with increasing number of languages (RTs) under the most complex condition (3-back) and the 3-0 (match) effect, but a more complex pattern was observed in terms of ACC. As with the Simon task, none of these were statistically significant, including any potential differences between bilinguals and trilinguals. Age only predicted ACC under the two easiest conditions (0-back and 1-back), showing improved accuracy of response with age. In terms of RTs, age only predicted the most complex condition (3-back) and several N-back effects, whereby slower RTs were linked with older age. However, what the results above show, statistically, regarding complexity is that both in terms of accuracy of response and reaction time, the groups did not statistically differ under any level of complexity, or increasing WM load between 0-back and the more complex conditions (1-back, 2-back and 3-back).

9.5 Discussion

The main aim of the present chapter was to provide new evidence regarding the level of cognitive control, and WM task complexity, and trilingualism. That is, whether the language group differences seen in Chapters 5 and 6 would become more pronounced with increasing level of complexity in the Simon task and the N-back task, and smaller with decreasing level of complexity (as tested with the N-back task). The same participants, aged 19 to 55 years, completed both tasks, and the language groups did not differ in terms of age, education or on SES measures. Language proficiency in the bilinguals' two languages, and trilinguals' three languages, did not differ.

9.5.1 Main findings

9.5.1.1 Simon task

All language groups performed comparably under the easy global accuracy condition, as well as in terms of monitoring and inhibitory control, under both easy and complex conditions of the task. The only language group difference observed was accuracy of response under the complex condition of the task, whereby bilinguals responded significantly less accurately than monolinguals. No differences between monolinguals and trilinguals, or bilinguals and trilinguals were observed.

No language group differences were observed in terms of age in the Simon task. Age predicted accuracy of response under both easy and complex conditions, where higher accuracy was observed in older participants. However, there was no effect of age under either easy or complex conditions in terms of RT.

The pattern seen under the simple condition is similar to the one seen in Chapter 5 (no language group differences in inhibitory control or monitoring, independent of age). Regarding complexity, the finding that bilinguals responded less accurately under the complex condition than monolinguals is not in line with the findings of Bialystok et al. (2004) or Salvatierra and Rosselli (2010), where accuracy was similar across language groups (monolinguals and bilinguals), both under the simple condition and the complex condition. The result that the language groups did not statistically differ on RTs (monitoring and Simon effect) under either the simple or the complex condition is surprising. The means indicate that both bilinguals and trilinguals responded more slowly than monolinguals; however this did not yield significance. This finding is not in line with Bialystok et al. (2004), who reported a bilingual advantage in inhibitory control under both simple and complex conditions. The younger age group in the study by Salvatierra and Rosselli (2010) covers a similar age range as in the present study (mean age for both is around 26 years). No inhibitory control differences were observed for that particular age group in Salvatierra and Rosselli (2010), under either the easy or complex condition. The present result is consistent with this, and suggests that the complexity of the task does not modulate performance of young adult to middle aged bilinguals or trilinguals.

9.5.1.2 N-back task

There was no significant main effect of language group on either the accuracy measures or reaction time measures in the N-back task. Importantly, the three language groups performed similarly across all four levels of complexity. There were, however, several trends observed, indicating a bilingual and trilingual disadvantage. By not holding non-verbal reasoning constant the results would have been the same.

No language group differences were found in terms of age in the N-back task. Accuracy was higher in older participants on easy conditions (0-back and 1-back) (on both match and non-match trials), but no effects of age were found for accuracy of response on the more complex conditions (2-back and 3-back). Regarding RTs, age-related decline was seen on the complex condition (3-back condition) only (both match and non-match trials), and on three N-back effects (2 minus 0 (non-match), 3 minus 0 (match and non-match)) where the magnitude of the N-back effect increased with age.

The finding of similar RTs between all language groups is not in line with what was observed in Chapter 6, where monolinguals were found to outperform trilinguals on most of the RT measures, and bilinguals on several. As this exact adapted version of the N-back task, with four levels, has not been used before in comparing trilinguals to bilinguals and monolinguals, it is not possible to make any concrete conclusions. Nevertheless, this result indicates, that in terms of RTs, monolingualism, bilingualism, and importantly, trilingualism do not modulate increasing WM demands in the N-back task.

The finding that accuracy of response did not differ between the groups on any of the four levels of the task, and on the N-back effects further suggests that increasing WM demands are not modulated by monolingualism, bilingualism and trilingualism.

Comparing young adult monolinguals and bilinguals on complex (operation span task) and simple (backward digit-span task and (non-verbal) symmetry span task) WM tasks Ratiu and Azuma (2014) did not observe a language group difference. Similarly, Bialystok et al. (2008) did not report a difference on forward and backward Corsi tasks, or self-ordered point task. However, Luo et al. (2013) observed a bilingual disadvantage on the alpha span task and a bilingual advantage on the forward and backward Corsi tasks. Bialystok et al. (2014 – study 2) on the other hand reported similar performance on a verbal version of the recent probe task, and a bilingual advantage on a non-verbal version of the same task, which was more complex in nature.

It is apparent that findings from WM tasks, comparing monolinguals and bilinguals, are rather elusive, on both simple and complex tasks. The evidence in the current study indicates that WM performance in trilinguals is not enhanced, or vice versa. This provides new evidence in this realm of research in terms of trilingualism, and of bilingualism.

9.5.2.1 Simon task and age effects

The finding that the level of accuracy on both simple and complex tasks improved with age is not in line with Bialystok et al. (2004). Salvatierra and Rosselli (2010) found no differences in accuracy between age-groups, and did not mention whether there was an age and accuracy interaction. Also, in Chapter 5, age was not found to predict accuracy of response.

In summary, no differences were detected between bilinguals and trilinguals, or trilinguals and monolinguals, in the Simon task. A bilingual disadvantage was, however, observed on the complex accuracy measure. Age predicted the accuracy measures, but not the RT measures. Discrepancies between the current study and the simple Simon task results in Chapter 5 and Bialystok et al. (2004) could be due to the fact that older participants in the present study were younger than in the research outlined Chapter 5 and that of Bialystok and colleagues (2004). The similar results reported here and for the younger age group in Salvatierra and Rosselli (2010) support this suggestion.

9.5.3.1 N-back task and age effects

The finding that both accuracy and RT performance was comparable between language groups regarding age is mostly in line with the finding in Chapter 6. One exception is that in Chapter 6, trilinguals found it significantly more difficult to cope with increasing WM demands between 1-back and 2-back in terms of accuracy of response. The present findings and those of Chapter 6 indicate that the relationship between WM capacity and ageing is mostly comparable between the language groups, as measured by the numerical N-back task.

In terms of RT, the finding that age only predicted the condition with the highest level of complexity – WM load (3-back) - and the N-back effects (between 3 and 0-back (match and non-match) and 2 and 0-back (non-match)), does not match the results from Chapter 6, which showed an age-related decline in both 1-back and 2-back. Also, this is not in line with the general finding of age-related slowing in processing speed (Salthouse, 2000), a drop in WM capacity (Bialystok et al., 2014; Cansino, 2013; Luo et al., 2013; Gazzaley et al., 2005; Bialystok et al., 2004; Missonnier et al, 2004) and previous N-back ageing studies (Saliasi et al., 2014; Schmiedek et al., 2009b; Nyberg et al., 2009). However, as mentioned in sub-section 9.5.2, this may be explained by the fact that the age range was not very large (19-55 years, mean age approximately 26 years) in the present sample. The finding that age-related decline only emerged under the most demanding condition indicates that in young and middle aged adults, WM capacity is not significantly taxed unless under considerably high WM load demand. The fact that there were only significant drops in performance between 0-back and 2-back, and 0-back and 3-back, further suggests that young and middle aged adults show similar WM capacity, unless under high WM load demands.

9.5.4 Methodological considerations

Perhaps this should not be considered as a methodological consideration as such, but the age range in the present study may not have been broad enough to explore age-related differences between the language groups. The present sample consisted of young to middle aged adults. As previously mentioned in this thesis, Hilchey and Klein's (2011) review concluded that the bilingual advantage is least likely to be seen in young adults (in terms of inhibition and monitoring). However, given that it has been previously suggested (Bialystok et al., 2012) that *"bilingual advantages for young adults tend to emerge on tasks or conditions that are difficult"* (Bialystok et al., 2012:6), and that the bilingual advantage only emerges under complex conditions (Bialystok et al., 2014; Morales et al., 2013; Bialystok, 2006), it was expected that language differences would be observed in the present chapter, although an opposite direction was anticipated due to previous findings in this thesis.

9.6 Conclusion

The present chapter aimed to shed some light on the speculation as to whether language group differences are more likely to emerge under complex (demanding) than simple conditions, and whether any differences found would increase with age. It was of particular interest whether this would apply to trilinguals. To the author's knowledge, for this purpose, the Simon task has not been previously used in trilinguals, and the numerical N-back task in bilinguals and trilinguals. The N-back task was chosen as it is capable of exploring WM load demands ranging from low up to very high. Some evidence exists for language group differences (between monolinguals and bilinguals) emerging under complex conditions (Bialystok et al., 2014; Morales et al., 2013; Bialystok, 2006). However, the present study provided new evidence for the opposite, that is increased task demands do not result in a language group difference, either in terms of inhibitory control (and monitoring) or WM capacity. The result that a bilingual disadvantage (compared to monolinguals) was only seen in accuracy of response under the complex condition of the Simon task is the only exception. Nevertheless, all things considered, it can be concluded that complexity (level of demands) may not be as strong a modulating factor as previous evidence suggests (Bialystok et al., 2014; Morales et al., 2013; Bialystok et al., 2012; Bialystok, 2006). It can be further concluded that young and middle aged monolinguals, bilinguals and trilinguals' performance is comparable and not affected by level of complexity. Future studies should replicate this, with a broader age range.

9.7 Chapter summary of key points

- Language group differences are not often seen in young adults.
- Previous research suggests that the bilingual advantage is more likely to be seen when task demands are high.
- This could explain the infrequent bilingual advantage observations in young adults.

- Based on previous points, language group differences should emerge in young adults (and middle aged adults) under complex conditions, with high task demands.
- The present study investigated this in monolinguals, bilinguals and trilinguals.
- The Simon task and numerical N-back task were utilised, and to the author's knowledge the Simon task has not been used for this purpose in trilinguals, and N-back task in bilinguals and trilinguals.
- The N-back task was chosen over other WM tasks as it is thought to tap into updating, and can include many different levels of complexity.
- The effects of age were also looked at.
- No language group differences were observed in terms of age, but on some measures age-related decline or improvement was seen. However, this was not consistent, which may be explained by the fact that the sample included young to middle aged participants.
- The only language group difference observed was in the Simon task, under the complex conditions, where bilinguals responded significantly less accurately than monolinguals.
- This suggests, at least in terms of accuracy, that in some cases language group differences emerge under complex conditions for this age range.
- Since this result was not consistent, it was concluded that complexity may not always be the key to seeing language group differences in young (and middle aged) adults.
- However, due to the fact that this is the first study investigating this aspect in trilinguals in the Simon task, and both bilinguals and trilinguals on the numerical N-back task, the result is yet to be confirmed.

Chapter 10: AoA and language use

10.1 Introduction

Some evidence suggests that (i) the L2 AoA and (ii) proficiency in L2 are factors which may influence performance on cognitive tests. For example, Mechelli et al. (2004) found that, compared to both monolinguals and late bilinguals, early and highly proficient bilinguals showed increased density of grey matter in the left inferior parietal cortex, a region assumed to be responsible for vocabulary acquisition.

Behavioural data also suggests that language proficiency may influence performance on non-verbal executive tasks, such as inhibitory control (Singh and Mishra, 2013 – L2 proficiency; Tse and Altarriba, 2012 – L1 and L2 proficiency) and target detection (Mishra et al., 2012 – L2 proficiency), although others have not found any evidence of L1 and L2 proficiency on Simon task and Trail making test performance (Goral et al., 2013) or L2 proficiency on task-switching performance (Xie, 2014). As the bilinguals and trilinguals in the present thesis reported relatively high and balanced proficiency in their languages, and language use has been found to be a stronger predictor of performance than language proficiency (Goral et al., 2013; Xie, 2014), the focus of the present investigation will be whether L2 AoA and language use predict performance in previous chapters in this thesis (5, 6, 7 and 8).

10.1.1 L2 AoA

The finding of Mechelli et al. (2004) is mostly in line with the literature on the cognitive benefits of bilingualism, whereby many of the bilingual advantages were observed in bilinguals who had acquired both their languages fairly early in life (see Tao et al., 2011). However, exceptions are accumulating (Zahodne et al., 2014; Ljungberg et al., 2013; Schroeder and Marian, 2012; Wodniecka et al., 2010; Bialystok et al., 2006), whereby a bilingual advantage was seen in older bilinguals who acquired L2 later in life. Tao et al. (2011) speculated whether this indicates that early acquisition is more important for young adults in terms of a cognitive benefit. However, as the next paragraph shows, counteractive evidence for this speculation exists, which, in an interesting way, demonstrates the complexity of bilingual experiences and their effects on cognitive performance.

Contradicting Mechelli et al.'s (2004) finding that early L2 AoA is important, Grogan et al. (2012) did not find such association in their bilingual group. A study by Linck et al. (2008 – study 1) reported an EF advantage (inhibitory control) in young adult L2 learners. The L2 learners can be categorised as late bilinguals, and have been classified as such in the present thesis, in which bilinguals and trilinguals acquired L2 from birth and onwards. Linck et al. (2008 – study 1) compared monolinguals (English) to four groups of L2 learners (Spanish); pre-immersion learners, immersed learners, post-immersion learners and classroom learners. The pre-immersion learners were taking an intermediate level language course to prepare for a semester abroad. The immersed learners were tested in their L2, after approximately three months after their arrival. The post-immersion learners were tested after they came back from the L2 environment. Lastly, the classroom learners studied L2 at a similar level as the other groups, but did not spend any time abroad. Linck et al. (2008) found that the L2 learners (all four groups together) outperformed the monolinguals in the Simon task, demonstrating a significantly smaller Simon effect. Furthermore, it was also observed that the classroom L2 learners demonstrated a significantly smaller Simon effect compared to the immersed L2 learner. These results indicate that the bilingual advantage, at least in terms of inhibitory control, is not only specific to early L2 AoA, and can be seen in young adults, even if they started learning the L2 at university level, and have not been immersed in the L2 environment. This further suggests that the bilingual advantage seen in some studies may be a result of cognitive exercise rather than as a result of managing two languages from early age (in young adults).

However, in contrast to Linck et al. (2008), another study did not find such effect in late bilinguals. Luk et al. (2011b) compared young adult early bilinguals, late bilinguals and monolinguals on a Flanker task (which also measures inhibitory control). The authors defined the bilinguals' acquisition as when they actively started using both their languages on a daily basis; they were considered early if they started using both languages actively before the age of 10, and late if after the age of 10. Both bilingual groups were significantly more proficient in their L1 than L2, the difference being larger in late bilinguals. Luk et al. (2011b) reported the smallest flanker effect (inhibitory control) for the early bilinguals and that late bilinguals and monolinguals demonstrated comparable performance.

Pelham and Abrams (2014) also compared young adult early bilinguals, late bilinguals and monolinguals, but on a different task; the attentional network task. Early bilinguals started acquiring L2 approximately eight years earlier than late bilinguals (early mean = 3.3 years, late mean = 11.6 years). Both types of bilinguals demonstrated comparable performance on the task, including inhibitory control performance, and both outperformed monolinguals in terms of inhibitory control.

The studies above suggest that the beneficial effects of managing two languages may not necessarily be dependent on the time when bilinguals started acquiring L2, although the result by Luk et al. (2011b) contradicts this view. The early versus late relationship was investigated by grouping the bilinguals into early versus late in Luk et al. (2011b) and Pelham and Abrams (2014). Treating the bilingual experience as a categorical variable may explain the contradicting results.

At least two studies have looked at the relationship between age of bilinguals' L2 AoA and cognitive performance, on a continuum. Both studies utilised a within group analysis (Soveri et al., 2011; Yow and Li, 2015), although neither study examined trilinguals or multilinguals. Soveri et al. (2011) examined 30 to 75 year old bilinguals, in which L2 AoA ranged from aged 8 to 25 years. They found that the age of L2 AoA predicted the RT of the Simon effect (with earlier acquisition associated with a smaller Simon effect), but not error rate. The authors investigated the effect of L2 AoA on inhibition measured by another task (Flanker task), on WM (visuospatial N-back task) and in shifting abilities, but did not find it to significantly predict any measures of these tasks. Yow and Li (2015) examined this in a younger group of bilinguals (18 to 25 year olds), whose L2 AoA was earlier (mean = 2.85 years). The authors did not give the actual range but stated that all participants acquired both languages before the age of seven. Like Soveri et al. (2011), Yow and Li (2015) investigated the influence of L2 AoA on performance on various EF tasks (Stroop task, Eriksen Flanker task, switching task and N-back letter task), which are thought to tap into inhibition, mental-set shifting and WM components. Yow and Li (2015) observed that L2 AoA only predicted the Stroop effect (inhibition) and the mixing cost in task-switching (thought to reflect global sustained control) where earlier acquisition was associated with a smaller Stroop effect and smaller mixing cost.

The findings of Soveri et al. (2011) and Yow and Li (2015) do indicate that, at least in terms of inhibitory control, the younger bilinguals acquire their L2 the stronger the inhibitory control. This was seen both in young adults who acquired L2 before the age of seven, and in middle-aged to older adults who had a larger range of L2 AoA. However, this was not seen on all the inhibition tasks (i.e., the Flanker task), and not consistently in other domains.

10.1.2 Language use

Indirect evidence indicates that language use may be an important predictor of performance on EF tests such as those utilised in the present thesis. For example, the bilingual participants in the studies by Bialystok et al. (2008; 2004), both of which reported a bilingual advantage, used both languages on a daily basis. Similarly, Salvatierra and Rosselli (2010) reported a bilingual advantage in the Simon task, and the bilinguals, who were not early starters (younger bilingual group: mean L2 AoA = 11 years; older bilingual group: mean L2 AoA = approximately 20 years) reported speaking both languages on a daily basis. Interestingly, Kousaie and Phillips (2011) reported a comparable performance in monolinguals and bilinguals in inhibitory control, despite the fact that the bilinguals reported being highly proficient in both languages and using both languages on a daily basis.

More direct evidence for the effect of language use on EF comes from studies such as that of Prior and Gollan (2011), who found that the amount of language switching influenced performance on task-switching performance. That is, the more frequent the language switching, the better the performance. Although this effect may well be specific to task-switching tasks, surely language switching is related to language use, as bilinguals who use both their languages to approximately the same extent throughout the day switch more often between them than those who use one language more than the other? A recent study by Xie (2014) suggests that this may be the case. Xie (2014) found that both language switching and language use could predict performance on a task-switching task (but interestingly, not L2 proficiency).

As far as I am aware, L2 AoA and language use has not been investigated in bilinguals and trilinguals on the tasks examined in the present thesis. Three recent studies investigated this in bilinguals and provided some evidence of language use predicting tasks other than those testing switching/shifting abilities. Those three studies also demonstrate that these abilities are not always predicted by language use. Soveri et al. (2011), who also investigated L2 AoA, (see section above) reported that language use predicted the flanker effect (inhibitory control) (RT but not error rates), although not RTs or error rates for the Simon effect (inhibitory control), N-back effect (WM) or set shifting. Goral et al. (2013) investigated the effect of language use on performance in the Simon task, the Trail making test (a measure of alternating attention) and the Month Ordering Span task (WM). They found that language use, measured on a continuum from balanced daily use of both languages to dominant daily use of one language, significantly predicted inhibitory control (Simon effect), with balanced bilinguals showing a *larger* magnitude of the Simon effect (contradicting the result of Soveri et al. (2011). However, they did not observe this on the other tasks. Lastly, Yow and Li (2015), who also tested L2 AoA (see section above), observed in their young adult bilingual group, that more balanced language use was associated with a smaller Stroop effect and smaller mixing cost. However, language use did not predict the switching cost, flanker effect (inhibition) or n-back effect (WM). The results from these three studies indicate that language use does impact bilinguals' performance. However, its effect is not consistent.

10.1.3 Summary

In sum, the evidence for the effect of L2 AoA and language use on EF performance is not at all consistent across tasks, domains (although the influence of the age of L2 AoA is most consistently seen in inhibitory control), or between studies. There is, however, conflicting evidence of the impact of early and late L2 AoA. Some studies suggest early bilinguals show a stronger inhibitory control (e.g., Yow and Li, 2015; Luk et al., 2011b; Soveri et al., 2011), whilst others suggest age of L2 AoA does not matter (Pelham and Abrams, 2014; Linck et al., 2008). One consistent finding is that Soveri et al. (2011), Goral et al. (2013) and Yow and Li (2015) found that language use predicted inhibitory control (although not on the same tasks). However, it is important to investigate this further, particularly when another language group is added to the investigation (trilinguals), which to the author's knowledge has not been previously investigated, nor has the impact of L2 AoA on trilinguals' EF performance.

10.2 Present study: research aims

Data sets from Chapters 5, 6, 7 and 8 were used to test whether bilinguals and trilinguals' performance can be predicted by L2 AoA and language use; Chapter 5 (The effects of trilingualism and ageing on inhibitory control and monitoring), Chapter 6 (The effects of trilingualism and ageing on WM performance), Chapter 7 (Trilingualism and ageing on inhibition of return) and Chapter 8 (Trilingualism and ageing on Stroop task performance). Both age of L2 AoA and language use were examined on a continuum as bilingualism should not be treated as a categorical variable. To the author's knowledge, this has not yet been explored in trilinguals.

Inhibition

Bilinguals: although conflicting evidence on the impact of L2 AoA on inhibitory control exists, the two studies (Yow and Li, 2015; Soveri et al., 2011) investigating this on a continuum suggest the earlier the better. Based on their results, it is hypothesised that the age of second language acquisition will influence the markers for inhibition, where stronger inhibitory control is associated with earlier acquisition of L2. In terms of language use, based on the contradictory findings of Yow and Li (2015), Goral et al. (2013) and Soveri et al. (2011), it was not clear whether or how language use influences test scores.

Monitoring and processing speed

Bilinguals: given that monitoring and processing speed has not directly been looked at, and in terms of the mixed results of other components, it was not clear how or whether acquisition of L2 and language use would predict monitoring.

WM

Bilinguals: based on previous findings it was hypothesised that language use and L2 AoA will not influence test scores in the N-back task.

Trilinguals (inhibitory control, monitoring and WM)

As (to the author's knowledge) this has not been examined in trilinguals, it was not clear whether the age of L2 AoA or language use would predict performance in trilinguals.

10.3 Methods

Participants under 65s were either students or staff at the University of Bradford, and participants over 65s were recruited from the University of Bradford participant pool.

10.3.1.1 Data set one (data from Chapter 5 - The effects of trilingualism and ageing on inhibitory control and monitoring)

The aim of this study was to investigate the bilingual advantage in monolinguals, bilinguals and trilinguals, and age effects with regard to inhibitory control and monitoring, using the Simon task. The sample comprised 132 participants (95 females and 37 males). Age effects were investigated on a continuum, with age ranging from 18 to 70 years (M = 29.86 years, SD = 13.80 years). Participants were separated into their three language groups; monolinguals (N = 40), bilinguals (N = 58) and trilinguals (N = 34).

10.3.1.2 Data set two (data from Chapter 6 - The effects of trilingualism and ageing on WM performance)

The aim of this study was to investigate the bilingual advantage, and age effects, on WM performance in monolinguals, bilinguals and trilinguals, utilising the N-back task. The sample comprised 142 participants (102 females and 40 males), who ranged in age from 18-79 years (M = 32.96, SD = 17.49). Participants were divided into groups of 48 monolinguals, 60 bilinguals and 34 trilinguals.

10.3.1.3 Data set three (data from Chapter 7 - Trilingualism and ageing on inhibition of return) and Chapter 8 (Trilingualism and ageing on Stroop task performance)

The aim of this study was to further investigate the bilingual advantage in inhibitory control and monitoring, as well as orienting, using the IOR and Stroop tasks, by comparing monolinguals, bilinguals and trilinguals. Age effects were also investigated. The sample consisted of 77 (49 females and 28 males) participants, ranging in age from 18 to 79 years (M = 39.45, SD = 20.70). Participants were divided into three groups of 31 monolinguals, 31 bilinguals, and 15 trilinguals.

10.3.2 Materials

Performance on the following tasks was analysed: the Simon task (Simon and Small, 1969), a sequential-numerical version of the N-back task (Gevins and Cutillo, 1993), IOR (Posner and Cohen, 1984), and the Stroop word-colour task (Trenerry et al., 1989). Detailed descriptions of these tests can be found in Chapters 5, 6, 7 and 8.

10.4 Results

The present study investigated whether age of L2 AoA and language use predicted bilinguals and trilinguals' performance on various EF tasks.

Table 15 shows the mean age, and range of L2 AoA for bilinguals and trilinguals, in all three data sets.

Table 15. Mean age of L2 AoA (L2 AoA), standard deviations (±SD) in brackets, and age range of the three data sets examined, in bilinguals (BL) and trilinguals (TL)

	Data set 1		**Data set 2**		**Data set 3**	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
L2 AoA (BL)	9.22 (7.68)	0-37	11.32 (7.82)	1-25	9.27 (7.88)	0-37
L2 AoA (TL)	4.21 (4.15)	0-18	4.80 (5.39)	0-18	4.61 (5.51)	0-27

Everyday use of both languages in bilinguals was calculated as the percentage of the less frequently used language subtracted from the percentage of the more frequently used language (Soveri et al., 2011). For trilinguals this was calculated as the percentage of the two least frequently used languages subtracted from the percentage of the most frequently used language (L1, L2 and L3 combined). A low score on this scale represents a balanced everyday use of languages, whereas a high score represents a less balanced use.

10.4.1 Data set one (Simon task)

10.4.1.1 Age of L2 AoA

To investigate whether L2 AoA predicted Simon task performance in bilinguals and trilinguals, the Simon effect and global RT were submitted to a multivariate GLM analysis as independent variables and age of L2 AoA as a covariate. The analysis revealed that age of L2 AoA did not statistically predict the Simon effect or global RT.

10.4.1.2 Language use

Language use was analysed separately for bilinguals and trilinguals, and thus the Simon effect and global RT were submitted to separate regression analyses, with language use as a predictor variable. The analyses revealed that for both bilinguals and trilinguals, daily language use did not statistically predict the Simon effect or global RT.

10.4.2 Data set two (IOR and Stroop tasks)

10.4.2.1 Age of L2 AoA

The same method of analysis as for data set one was used to test whether the age of L2 AoA predicts performance on the IOR and Stroop tasks. The analyses for both the IOR and Stroop task revealed that the age of L2 AoA did not predict any of the measures.

10.4.2.2 Language use

The same method of analysis as in data set one was used to investigate whether everyday language use of bilinguals and trilinguals predicts the measures on the inhibition of return task and the Stroop word-colour task.

IOR

Language use did not predict bilinguals' performance in the IOR task. In trilinguals, language use marginally predicted the global accuracy in the IOR task ($F(1, 13) = 4.55$, $p = .053$), whereby correlation analysis suggests higher accuracy with more dominant use of the trilinguals' three languages ($r = .39$, $p = .053$).

Stroop

The analyses revealed a significant main effect of language use for bilinguals in the congruent condition ($F(1, 29) = 4.16$, $p = .051$). For trilinguals, there was also a significant main effect of language use in the congruent condition ($F(1, 13) = 5.47$, $p <.04$), and a trend on the Stroop effect ($p = .064$).

The regression analysis for the ***bilinguals*** revealed that language use significantly predicted performance on the ***congruent condition*** [$\beta = 69.43$, SE = 2.77, ($F(1, 29) = 4.16$, $p = .051$), y axis intercept = .10 (SE = .05), with regression correlation coefficient $r = .35$, $p < .03$], revealing a better performance with less balanced use of bilinguals' two languages. For ***trilinguals***, the regression analysis also revealed that language use significantly predicted performance on the ***congruent condition*** [$\beta = 56.52$, SE = 7.24, ($F(1, 13) = 5.47$, $p < .05$), y axis intercept = .27 (SE = .11), with regression correlation coefficient $r = .54$, $p < .02$], whereby better performance was associated with less balanced use of trilinguals' three languages. Correlation analysis suggests a smaller Stroop effect with more balanced use of trilinguals' three languages ($r = .49$, $p = .064$)

10.4.3 Data set three (N-back task)

10.4.3.1 Age of L2 AoA

The same method of analysis as for previous data sets was used to investigate the impact of age of L2 AoA on N-back performance. The analysis revealed that the age of L2 AoA was not found to predict performance in the N-back task.

10.4.3.2 Language use

The same method of analysis as in previous data sets was applied here. The accuracy scores were not predicted by language use, in either bilinguals or trilinguals. In terms of the RT measures for bilinguals, a main effect of language use was found for 2-back (non-match) ($F(1, 57) = 6.47$, $p < .02$) and n-back effect (non-match) ($F(1,157) = 5.45$, $p < .03$), Trends were seen for 1 back match and non-match and 2 back match.

Regression analyses revealed positive, significant linear relationships with language use and ***2-back*** (non-match)($\beta = 605.55$, ($F(1,57) = 6.47$, $p < .05$), y axis intercept = 3.27, with regression correlation coefficient $r = .32$, $p < .01$) whereby RT increased with more dominant use of one language, and with the ***n-back effect*** (non-match)($\beta = 43.70$, ($F(1,57) = 5.45$, $p < .03$), y axis intercept = 2.28, with regression correlation coefficient $r = .3$, $p < .02$) whereby the magnitude of the n-back effect increased with more dominant use of one language. For trilinguals, language use did not predict any of the RT measures.

10.4.4 Summary

L2 AoA did not predict any of the test scores across the language tasks. Language use did not predict the test scores in the Simon task, or the IOR task. In the Stroop task, language use only predicted numbers of words read in the congruent condition (for both bilinguals and trilinguals), where better performance was associated with more dominant use. In the N-back task language use did not predict trilinguals' test scores, but predicted two non-match scores, where more balanced use was associated with better performance. See Table 16.

Table 16. Overview of bilinguals (BL) and trilinguals' (TL) L2 AoA and language use on the tasks examined in the present study

Task	L2 AoA	Language use
Simon task	X	X
IOR task	X	X
Stroop task	X	BL/TL = congruent*
N-back task	X	BL = 2-back and n-back effects (non-match)**, TL = X

* = the more dominant use the better the performance, ** = the more balanced use the better the performance

10.5 Discussion

The aim of the present study was to examine whether performance of bilinguals and trilinguals' various EF tasks [Simon task, IOR task, Stroop task and the N-back task (probing the following components: inhibition, monitoring, processing speed and WM)] could be predicted by age of L2 AoA and language use. To the author's knowledge, this is the first study to investigate these two variables in relation to trilinguals' performance on these tasks, as well as for bilinguals on the numerical N-back task and the IOR task, and lastly, monitoring and processing speed for both language groups. As a reminder, both language groups were equally proficient in their L1 and L2 in all three data sets. Also, according the picture naming task in Chapters 7 and 8 (data set two), bilinguals picture naming performance in L1 and L2 was comparable, as was trilinguals picture naming performance in L1, L2 and L3.

10.5.1 Main findings

For both bilinguals and trilinguals, L2 AoA did not predict any of the test scores on any of the tasks examined here.

Language use did not predict the test scores in the Simon task or the IOR task, for either language group. In the Stroop task, only performance on the congruent condition (processing speed) was predicted by language use, where both language groups demonstrated better performance with more dominant use. Language use did not predict N-back performance for trilinguals, but for bilinguals, 2-back and n-back effect (both non-match) scores were predicted by language use, where more balanced use was associated with better performance.

10.5.2 L2 AoA

The consistent finding that L2 AoA did not predict the test scores on the Simon and N-back tasks, suggests that the L2 AoA is not more important for young adults than older. Nevertheless, given that L2 AoA has been implicated in other studies, it is essential that these variables should be taken into consideration when interpreting findings on the effect of bilingualism and trilingualism on cognitive performance.

This is not in line with Soveri et al. (2011) and Yow and Li (2015), who observed a stronger inhibitory control performance with earlier acquisition of L2. Neither does this finding match other studies, which have reported a bilingual cognitive advantage in bilinguals who acquired L2 early in life (see Tao et al., 2011). However, Soveri et al. (2011) examined L2 AoA on other four measures (including inhibition and WM) and did not find L2 AoA to predict those. Taken together, these findings indicate that early L2 AoA do not necessarily equal better performance, and that L2 AoA is not an important factor for WM, but can be for inhibitory control.

The contradicting findings from the present analysis and Soveri et al. (2011) regarding the Simon effect may be due to the fact that the bilinguals in Soveri et al. (2011) were all early simultaneous (learned both languages simultaneously from birth) bilinguals, aged 30 to 75, but in the present analysis the bilinguals were both simultaneous, and early and late sequential bilinguals, aged 18 to 79. The lack of the effect of L2 AoA is unlikely to be due to the fact that this was measured on a continuum as opposed to dividing participants into early versus late acquisition groups. Soveri et al. (2011) used the same method and still observed an effect of L2 AoA.

10.5.3 Language use

10.5.3.1 Data set one (Simon task)

The finding that daily language use did not predict performance in bilinguals or trilinguals in the Simon task confirms the results obtained by Soveri et al. (2011) that bilinguals' inhibitory control was not predicted by language use type. The bilinguals (mean = 44.81) and trilinguals (mean = 45.50) in the current sample were slightly more balanced than dominant and the results are, therefore, only partly in line with the findings of Goral et al. (2013), that dominant bilinguals showed little or no age-related decline in inhibitory control, whereas balanced bilinguals showed an age-related decline in inhibitory control. Neither Goral et al. (2013) nor Soveri et al. (2011), investigated this in terms of global RT.

10.5.3.2 Data set two (IOR and Stroop tasks)

The observation that language use did not predict IOR task performance in bilinguals and not consistently in trilinguals is in line with the finding in the Simon task.

The finding that for both bilinguals and trilinguals, language use predicted performance on the congruent condition (processing speed) in the Stroop task is partly in line with Goral et al. (2013). What is similar is the fact that, as was seen in the bilinguals in Goral et al. (2013), the more dominant language use bilinguals and trilinguals reported the better their performance. However, what was different was the fact that in the present study this was seen in terms of processing speed, whilst in Goral et al. (2013) it was seen in terms of inhibitory control (Simon effect). This suggests that different characteristics of language experience may affect various mechanisms of cognitive control in bilinguals, and trilinguals, in divergent ways. This fits with Green's (2011) conclusion, where he suggests that the differences in bilinguals' life experiences may lead to varying mechanisms of language control which, in turn, may result in different cognitive control advantages in bilinguals. This may also suggest, regarding certain mechanisms, that the more dominant use of one language on a daily basis results in stronger cognitive control.

10.5.3.3 Data set three (N-back task)

As in the study by Soveri et al. (2011) the present analysis showed that language use did not predict any of the accuracy measures, in either bilinguals or trilinguals. In fact, it did not predict any measures in trilinguals. In terms of RT, language use predicted 2-back and n-back effect (both non-match) in bilinguals, indicating a slower RT and a larger n-back effect with a more dominant use of one language. It is not clear why language use only predicted the aforementioned measures, and in bilinguals only. The observation that language use only predicted 2-back scores may indicate that only under complex conditions language use matters. Also, the fact that language use did not predict match, but only non-match, may also indicate that it is only relevant under certain conditions. The match (stimulus detection/recognition) and non-match (active stimulus processing) trials are thought to reflect different underlying processes (e.g., Palomaki et al., 2012; Chen et al., 2008; Pesonen et al., 2007).

10.5.4 Methodological considerations

The present study looked at whether the age of L2 AoA could predict performance in both bilinguals and trilinguals. However, the age of L3 AoA was not examined in the three data sets under investigation here. In the study reported in Chapter 9 (The effects of trilingualism and complexity on inhibitory control, monitoring and WM capacity), trilinguals were asked to report the age of L3 AoA, and a MANCOVA analysis revealed that L3 did not predict any of the Simon task or N-back test scores in Chapter 9. Although, comparable to L2 AoA, this suggests that the age trilinguals start acquiring their L3 does not predict their performance on the Simon and N-back tasks, this needs further testing.

10.6 Conclusion

The present study examined whether L2 (and L3) AoA and language use are important predictors of performance on the inhibition and WM tasks in the present thesis. Neither acquisition nor language use were found to be reliable predictors of performance, although language use is slightly more so. These findings echo previous evidence, pertaining to bilinguals, which is not conclusive, and provide new evidence relating to trilinguals, showing little or no relationship between trilingualism and L2 AoA, and language use, respectively. The findings further suggest that other influencing factors are at play, and may even override the effects of language acquisition and language use. Further research is needed to determine whether other bilingual and trilingual experiences, or alternative confounding factors, may be more important for performance.

10.7 Chapter summary of key points

- Some evidence indicates that L2 AoA and language use affect bilinguals' performance, although this is not conclusive.

- The present study investigated this in bilinguals, and trilinguals on three types of inhibition tasks (Simon, Stroop and IOR) and one WM task.
- This type of study, investigating trilinguals, has to the author's knowledge not been previously published.
- Also, L3 AoA has to the author's knowledge not been previously examined in relation to Simon task and numerical N-back task performance, although this was not thoroughly examined here, and further testing is needed.
- The age of L2 AoA did not predict performance in either bilinguals or trilinguals, nor did L3 AoA for the trilingual group.
- Language use did not consistently predict the test scores for bilinguals (and not at all for trilinguals), and its effects were only seen in the WM study for the 2-back and the n-back effect (both non-match), where more dominant use of one language was associated with worse performance, which I argue relates to the complex nature of these trials.
- The present study provides new evidence that L3 AoA does not predict cognitive control or WM capacity.
- The present study did not find evidence supporting that L2 AoA influences performance in trilinguals, suggesting that L2 AoA is not an important factor with regard to EF.
- These results suggest that L2 and L3 AoA, and language use are not consistent predictors of performance, although language use is slightly more so. However, this needs to be clarified in future studies.

Chapter 11: Confounding factors

11.1 Introduction

One of the main limitations of studies investigating the effects of bilingualism is the influence of possible hidden elements, such as demographic factors, which are thought to affect cognition (Hilchey and Klein, 2011). As is true for all quasi-experimental study designs, monolingual, bilingual and trilingual participants cannot be randomly assigned to groups, and therefore it is difficult to determine whether significant language group differences are due to genuine differences between the groups, or to other confounding factors. Hence, this is a persistent issue with all studies looking into the effects of bilingualism, or trilingualism on cognition (when comparing different language groups), and consequently, alternative explanations for findings need to be considered, and controlled for (Hilchey and Klein, 2011; Harris et al., 2006).

One way to control the effects of possible hidden factors is to determine which factors are associated with the variables under investigation. This can be done by either matching the language groups on these factors, or controlling for them in the analysis. Some published studies (and previous chapters of the present thesis, if the language groups differed), which investigated the effect of bilingualism on cognitive functioning, controlled for hidden factors, such as age and SES (see for example Pelham and Abrams, 2014; Tao et al., 2011). These are thought to co-vary with executive ability (e.g., Mezzacappa, 2004). Nevertheless, accumulating evidence suggests that the bilingual advantage in cognition is independent from socioeconomic background, and the level of proficiency of bilinguals' languages (Blom et al., 2014; Calvo and Bialystok, 2014; Carlson and Meltzoff, 2008; Engel de Abreu et al., 2012). Do we know, however, where the boundaries to these possible hidden factors lie? The present chapter will examine two possible modulating factors; cognitive activity (CogA) and physical activity (PhysA). As seen in Chapter 2 of the present thesis, mounting evidence suggests, as often is found regarding bilingualism, that engaging in PhysA and CogA enhances cognitive functioning and that this is not limited to older adults. I will now introduce each one in turn.

11.1.1 PhysA

Neural and behavioural evidence shows that both long term and short term aerobic exercise (including walking), has beneficial effects on the brain due to increased cerebral blood flow, which in turn improves neuronal connectivity (Burzynska et al., 2014; Erickson et al., 2013; Tseng et al., 2013; Voss et al., 2013; Hillman et al., 2008; Colcombe et al., 2006) and cognition (Hogan et al., 2013; Smith et al., 2013; Verburgh et al., 2013; Weuve et al., 2004; Colcombe and Kramer, 2003). This is important for EFs, which are associated with the frontal lobes, mostly in the prefrontal cortex, as well as other regions (Jurado and Rosselli, 2007). White matter is responsible for the connectivity between brain regions, where stronger connectivity means faster information transfer, resulting in better executive performance (Filley, 2010). Interestingly, studies have found that like physical exercise, early lifelong bilingualism affects the structure of white matter, which consequently slows down its age-related deterioration (Gold et al., 2013; Luk et al., 2011a). Similar effects have recently been observed in young bilinguals, who acquired their L2 later in life but have actively used both languages (Pliatsikas et al. 2014). See more detail in Chapter 4.

11.1.2 CogA

Evidence suggests that engagement in cognitively stimulating activities, such as reading, writing, attending lectures, word games, crossword puzzles, and card games, both early and later in life, is associated with enhanced cognitive function, and consequently reduces age-related cognitive decline (Wilson et al., 2013; Reed et al., 2011; Lachman et al., 2010; Plassman et al., 2010; Stern, 2009; Sing-Manoux et al., 2003).

Cognitive training interventions have also been shown to have beneficial effects on cognition. A meta-analysis from RCTs (Valenzuela and Sachdev, 2009) investigated the effect of cognitive exercise on longitudinal cognitive performance in healthy older adults. The reviewed studies included interventions such as reasoning training and information processing, speed, memory, and problem solving training. Valenzuela and Sachdev (2009) reported a positive effect of cognitive exercise on cognitive performance, with the data also suggesting that just two to three months of cognitive exercise may result in long-lasting and persistent effects on cognitive performance, in the healthy elderly.

11.1.3 Hidden factors, cognition and bilingualism

Video game playing (Bialystok, 2006) and musical experience have been suggested to enhance EF (Moradzadeh et al., 2014; Bialystok and Depape, 2009), although the effects have been explored within limited domains thus far. Moradzadeh et al. (2014) examined the association between musical training, bilingualism, task-switching and dual-task performance. Young adult monolinguals and bilinguals were divided into four groups; monolingual musician (N = 45), bilingual musician (N = 36), monolingual non-musician (N = 36) or bilingual non-musician (N = 36). The participants were matched on both age and SES.

Moradzadeh and colleagues (2014) reported that long term musical training was associated with enhanced task-switching and dual-task performance. Interestingly, bilinguals did not demonstrate any advantages. There was no interaction between language group and music group either, but this may have been due to the fact that there was not an effect of bilingualism anyway (Moradzadeh et al., 2014). These findings indicate that other life experience factors than bilingualism modulate cognitive processing, which in turn suggests that bilingualism may simply be a cognitive “training” effect, although this view does not explain the fact that the cognitive enhancement effects of bilingualism seem to be more specific than general.

Given that Moradzadeh et al. (2014) looked at musical training, this was also investigated here. However, based on the small numbers in each sub-group reporting instrument playing (five monolinguals, three bilinguals and three trilinguals) it was impossible to examine any group differences or to determine conclusive effects. Nonetheless, a Multivariate GLM analysis revealed possible effects of two of the six musical experience factors under investigation (overall musical ability and the age when participants started musical training – see Appendix 2 for the remaining factors) on inhibitory control. No effects were detected in WM performance or non-verbal reasoning. However, the only significant regression showed an association between the age participants started musical training and inhibitory control (Simon task), whereby stronger inhibitory control was associated with earlier start of musical training ($r = .76$, $p <.01$). This is in line with findings by Bialystok and Depape (2009) and Moradzadeh et al. (2014), although due to sample size this will need further testing.

11.1.4 Bilingualism, PhysA and CogA

As far as I am aware, this is the first study looking into the modulating effects of CogA and PhysA on monolinguals, bilinguals and trilinguals' performance on EF tasks. However, related to this, Bialystok et al. (2014) investigated whether the proposed protection of bilingualism against onset of displayed symptoms in AD would extend to mild cognitive impairment (MCI), after controlling for certain lifestyle factors. They confirmed previous findings of bilinguals displaying the onset of symptoms of AD (and first visit to clinic) several years later than monolinguals, and this between-group difference was also extended to MCI. Bilingual and monolingual participants also completed three EF tests (Trail making test, Stroop colour-word Task and verbal fluency), in which performance was found to decline over three sessions (over one year), with no between-group difference in the decline. In terms of the lifestyle factors under investigation, which included social activity and PhysA, they did not investigate any direct effects of these factors on the EF tests. They only reported whether these factors modulated the finding of delayed symptoms, and date of first clinic visit, and concluded that these factors did not have modulating effects (Bialystok et al., 2014).

Similarly, another recent study (Brewster et al., 2014) investigated a wide range of life experiences (including CogA and PhysA, and bilingualism) on longitudinal cognitive trajectories in older adults. They reported some beneficial effects of PhysA on cognition, but interestingly no difference between monolinguals and bilinguals on cognitive performance. Like Bialystok and colleagues (2014) they did not examine the bilingualism x CogA and PhysA relationship, but tested their influence on cognition as separate measures.

11.1.5 Summary

Although the overall evidence of both PhysA and CogA indicates a beneficial effect, understanding of which cognitive domain or domains benefit the most from a given activity remains incomplete. Nevertheless, the above studies suggest that short term and long term PhysA enhances structural plasticity and cognitive function, including EF. Evidence for such enhancement has also been demonstrated regarding CogA, both training and traditional forms of cognitive stimulation (e.g., doing crossword puzzles). Hence, as with all studies investigating the relationship between bilingualism/trilingualism and cognition, it is important to investigate whether these factors can explain any of the effects found in previous chapters in this thesis (5, 6, 7 and 8).

11.2 Present study: research aims

The present study investigates whether the level of CogA and PhysA can explain the significant between group differences found in Chapter 5 (The effects of trilingualism and ageing on inhibitory control and monitoring), Chapter 6 (The effects of trilingualism and ageing on WM performance), Chapter 7 (Trilingualism and ageing on inhibition of return) and Chapter 8 (Trilingualism and ageing on Stroop task performance). Chapters 7 and 8 were derived from the same dataset.

11.3 Methods

The data analysed here are from the same three datasets as in Chapter 10. Data set one: Chapter 5 'The effects of trilingualism and ageing on inhibitory control and monitoring'. Data set two: Chapter 7 'Trilingualism and ageing on inhibition of return' and Chapter 8 'Trilingualism and ageing on Stroop task performance'. Data set three: Chapter 6 'The effects of trilingualism and ageing on WM capacity'. Please refer to the method section in Chapter 10 and methods sections of the above-mentioned chapters for more detailed information. The language groups did not statistically differ in terms of either CogA or PhysA in any of the data sets.

11.3.2 Materials

The possible CogA and PhysA confounding factors were obtained from the lifestyle questionnaire. The following PhysA factors assessed for all three data sets were (i) aerobic exercises (hours per week) and (ii) walking (hours per week). See Appendix 1 for more details. These were combined into an average composite score and will be referred to as PhysA from now on. The CogA factors were (i) Sudoku playing, (ii) doing crosswords, (iii) playing cards (participants reported playing specific types, such as solitaire and bridge), (iv) playing Scrabble, and (v) brain training and computer/video game playing. All were rated on a scale of 1 to 7 (1 = every day, 2 = 4-5 times per week, 3 = 2-3 times per week, 4 = once per week, 5 = 2-3 times per month, 6 = once per month, 7 = less often). See Appendix 1 for more details. As with PhysA these were combined into an average composite score, and will be referred to as CogA from now on.

11.3.3 Design

The measures under investigation, in which between group differences were found in Chapters 5, 6, 7 and 8, can be seen in Table 17.

Table 17. Overview of the measures on which language group differences were found in Chapters 5, 6, 7 and 8

Task	Measure	Reflects
Simon task	Simon effect RT	Inhibitory control
N-back task	1-back match RT	Lower WM load
	1-back non-match RT	Lower WM load
	2-back match RT	Higher WM load
	2-back non-match RT	Higher WM load
	N-back (match) effect ACC	The cost of managing increasing updating demands
IOR task	Global RT	Monitoring
Stroop task	Incongruent	Inhibitory control
	Stroop effect	Inhibitory control

11.4 Results

The aim of this study was to investigate whether the significant language group differences on three datasets can be explained by either the level of engagement in CogA, or PhysA. Many researchers state that there may be confounding factors in studies of bilingualism and cognition. Any language group x CogA/PhysA or language group x age x CogA/PhysA interactions would suggest that these factors influenced performance, and thus only these are focused on here.

11.4.1 Data set one (Simon task – Chapter 5)

10.4.1.1 Interactions between language group x CogA/PhysA on the Simon effect

In order to assess language group, and any interaction with CogA and PhysA, the Simon effect score was submitted to ANCOVA as a dependent variable, with language group as a fixed factor, and CogA and PhysA as covariates. No interactions between language group and CogA or PhysA were observed.

11.4.1.2 Language group x age x CogA/PhysA interactions on the Simon effect

In order to assess any interactions between language group, age and CogA and PhysA on performance, an ANCOVA was carried out with language group as fixed factor, age and CogA and PhysA as covariates, and the Simon effect score as a dependent variable. There were no significant interactions between language group, age, and CogA or PhysA on the Simon effect.

11.4.2 Data set two (N-back task – Chapter 6)

11.4.2.1 Interactions between language group x CogA/PhysA on N-back scores

In order to assess language group, and any interaction with CogA and PhysA, the N-back scores were submitted to MANCOVA as dependent variables, with language group as a fixed factor and CogA and PhysA as covariates. Significant interactions were present between language group and PhysA on 1-back match RT ($F(2,120) = 4.55$, $p < .02$) and 1-back non-match RT ($F(2,120) = 5.50$, $p = .005$). Scatter plots of these interactions can be seen in Figure 14.

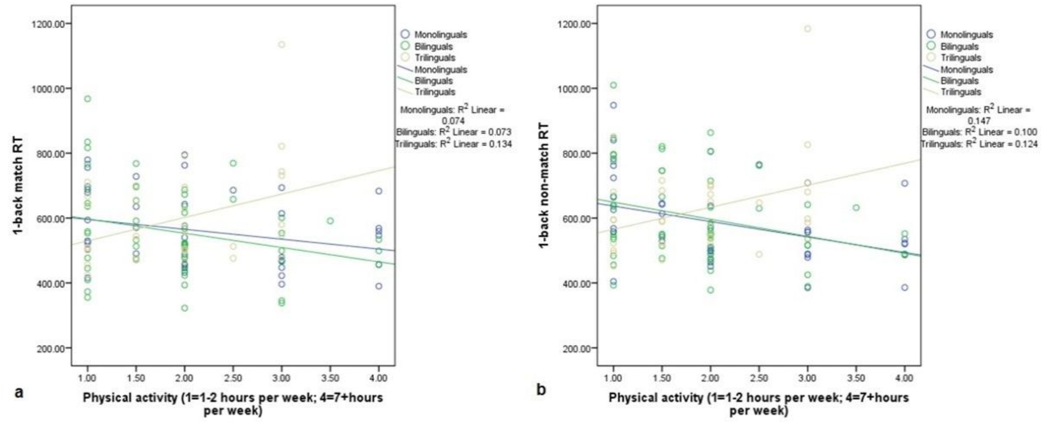

Figure 14 depicts significant interactions between language groups, PhysA and (a) 1-back match RT and (b) 1-back non-match RT. Monolinguals and bilinguals' RTs decreased with increased level of PhysA, whereas trilinguals' RTs increased with increased level of PhysA.

11.4.2.2 Language group x age x CogA/PhysA interactions on N-back scores

To assess any interaction with CogA and PhysA, the N-back scores were submitted to MANCOVA as dependent variables, with language group as a fixed factor and age, CogA and PhysA as covariates. Significant three-way interactions between language group, age, and PhysA were present for 1-back match RT ($F(3,117) = 2.67$, $p = .05$) and 1-back non-match RT ($F(3,117) = 2.85$, $p < .05$). By median split (25 years) the groups were divided into "young monolinguals", "young bilinguals", "young trilinguals", "older monolinguals", "older bilinguals" and "older trilinguals". See Figure 15 for these interactions.

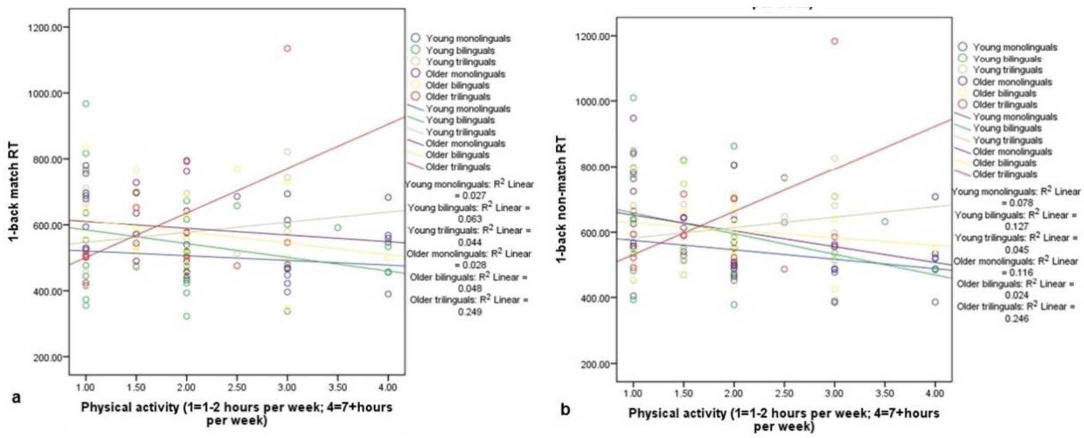

Figure 15 depicts the significant interactions between age x language group x PhysA for (a) 1-back match RT and (b) 1-back non-match RT. Older trilinguals demonstrate slower RTs with more PhysA engagement on both measures. Young trilinguals show a similar pattern, but not as pronounced. The other groups all show faster RTs with increased PhysA engagement, although not a strong association.

11.4.3 Data set three (IOR task – Chapter 7, and Stroop task – Chapter 8)

10.4.3.1 Interactions between language group x CogA/PhysA on IOR and Stroop task scores

Following the same method of analysis as in previous sections, significant interaction between language group and PhysA was observed for IOR global RT (F (2, 61) = 4.09, p< .03). See Figure 16.

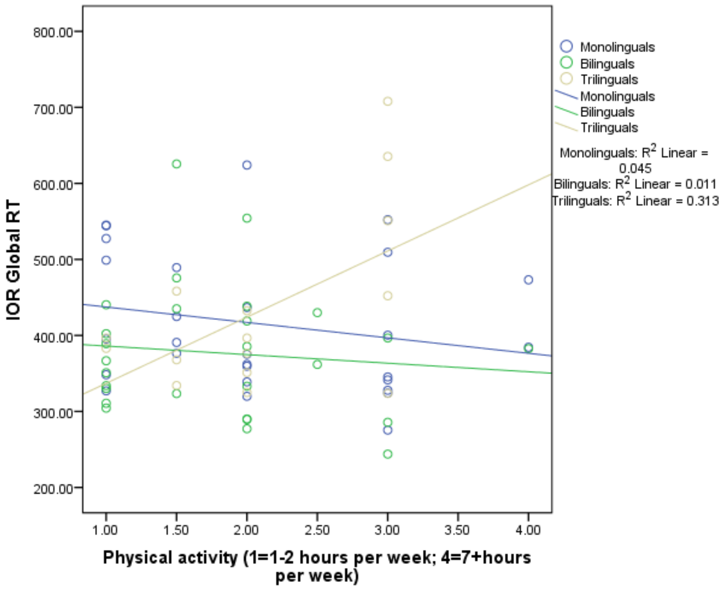

Figure 16 depicts the significant interaction between language group x PhysA on global RT, where monolinguals and bilinguals' RTs slightly decrease with increased PhysA, whereas trilinguals show a steep increase in RTs with increasing PhysA.

11.4.3.2 Language group x age x CogA/PhysA interactions

No three-way interactions were found in the IOR task or the Stroop task.

11.4.4 Summary

As can be seen in Table 17, language group differences were not influenced by CogA on any of the test scores. PhysA did not influence the language group differences on the Simon effect, the incongruent condition (Stroop), the Stroop effect, or the 2-back, or N-back effect measures. However, there were significant language group x PhysA interactions for 1-back (match and non-match) where monolinguals and bilinguals' RTs decreased with more PhysA but trilinguals' RTs ***increased*** with more PhysA, and a significant language group x age x PhysA interaction showed that the increasing RTs in trilinguals were observed in older trilinguals. A significant language group x PhysA interaction was also seen for IOR global RT, where trilinguals demonstrated ***increasing*** RTs with more PhysA, but the opposite pattern for the other language groups.

Table 17. Overview of the measures on which language group differences were found in Chapters 5, 6, 7 and 8, and significant language group x PhysA (✓) and significant language group x age x PhysA interactions (✓✓)

Between group differences	**CogA**	**PhysA**
Simon task		
Trilingual disadvantage on the Simon effect	X	X
N-back task		
BL disadvantage on 1-back M	X	✓/✓✓
BL disadvantage on 2-back NM	X	X
TL disadvantage on 1-back M/NM	X	✓/✓✓
TL disadvantage on 2-back M/NM, and N-back (M) effect	X	X
IOR task		
Trilingual disadvantage in global RT	X	✓
Stroop task		
Trilingual disadvantage on incongruent condition	X	X
Trilingual disadvantage on the Stroop effect	X	X

BL = bilinguals, TL = trilinguals, M = match, NM = non-match

11.5 Discussion

The aim of this study was to examine the influence of PhysA and CogA engagement on performance, from three data sets of this thesis.

Researchers in the bilingualism and cognition literature maintain that confounding factors may influence the results. Hence, it is imperative to test for this here. As far as I am aware, this is the first study which attempts to examine the direct modulation effects of CogA and PhysA in monolinguals, bilinguals and trilinguals' EF.

11.5.1 Main findings

CogA did not influence the test scores under investigation on any of the tasks. This suggests that CogA did not explain any of the language group differences found on the three datasets.

The trilingual disadvantage (compared to monolinguals and bilinguals) on the Simon effect (dataset 1), in older than 29 years old, could not be explained by PhysA because the present analysis did not find a language group and PhysA interaction (or language group x age PhysA interaction). For the same reason, the trilingual disadvantage (compared to monolinguals) on incongruent condition in the Stroop task could not be explained by PhysA.

1-back match and non-match RTs decreased with increasing PhysA for monolinguals and bilinguals, but increased for trilinguals. Three way (age x language group x PhysA) further revealed that it was the older trilinguals who showed increasing 1-back RTs with increasing PhysA.

Trilinguals' global RT in the IOR task increased with increasing level of PhysA, and monolinguals and bilinguals' RTs decreased with increasing level of PhysA.

11.5.2 No effect of CogA on language group differences

The finding that CogA did not predict any of the test scores under investigation is not in line with studies showing that engaging in CogA exerts beneficial effects on cognitive performance (Wilson et al., 2013; Reed et al., 2011; Lachman et al., 2010; Plassman et al., 2010; Stern, 2009; Sing-Manoux et al., 2003). A closer look at the data may, however, explain this as it is clear that most participants in the studies reported little cognitive engagement. On a scale of one to seven, the overall mean was 6.17 (on this scale six is once per month and seven is less often). This alternative explanation is reasonably probable as a review by Hertzog et al. (2009) concluded that CogA is a stronger predictor than PhysA when it comes to cognitive benefits.

11.5.3 No effect of PhysA on Simon effect or Stroop effect

The findings that neither the Simon effect nor the Stroop effect, nor the incongruent condition in the Stroop task, were influenced by PhysA, indicate that for the present sample the language groups' inhibition mechanisms are not modulated by PhysA.

11.5.4 Are 1-back scores and IOR global influenced by PhysA?

In Chapter 6, in the N-back task, a trilingual disadvantage (compared to monolinguals) was observed on both 1-back and 2-back, on both match and non-match trials. A bilingual disadvantage (compared to monolinguals) was also observed in the N-back task, although only on 1-back and 2-back non-match trials. The finding that 1-back match and non-match RTs (both a lower level of WM load) decreased with increasing PhysA, for monolinguals and bilinguals, but increased for older trilinguals, may explain why trilinguals were outperformed by monolinguals. Furthermore, the language group differences on 1-back were independent of age (there was no language group x age interaction on any of the N-back measures). Therefore, the older trilinguals' slowing down in RTs with increased PhysA is unlikely to have influenced the observed differences between trilinguals and monolinguals. Given no differences in the 2-back condition, shows that any influence PhysA may have had is only in the simple condition.

A trilingual disadvantage (compared to monolinguals) was found in global RT in the IOR task (Chapter 7), and this effect was independent of age. The finding that both monolinguals and bilinguals responded faster with increasing PhysA, but trilinguals responded slower with increasing PhysA (IOR global RT), indicates that the trilingual disadvantage in IOR global RT (Chapter 7) may have been influenced by trilinguals PhysA. This further suggests that when comparing these three language groups, PhysA needs to be taken into consideration.

The finding that monolinguals and bilinguals' RTs decreased with increasing level of PhysA whereas trilinguals' RTs increased with increasing level of PhysA is intriguing. Nevertheless, a recent systematic review of twelve RCTs on the effect of PhysA (aerobic) on cognition did not find conclusive evidence that PhysA offered cognitive benefits in healthy older adults, even though it improved their level of cardiorespiratory fitness (Young et al., 2015). This suggests that the relationship between PhysA and cognition may be influenced by other factors, which were not assessed here. For example, how socially active the participants were may have confounded the results, as this too has been found to be positively linked to cognition (Wang et al., 2012). It could have been the case that the monolinguals and bilinguals were more socially active than the trilinguals, and should this possible link be considered in future studies.

11.5.5 Methodological considerations

There are several methodological considerations to note. As is true for all studies reported in this thesis, this study is based on cross-sectional data and therefore cannot offer conclusive evidence about directionality. To obtain a better understanding of how CogA and PhysA modulate cognitive performance in monolinguals, bilinguals and trilinguals a longitudinal study would be necessary. However, longitudinal studies have their limitations, such as practice effects. Also, the measures of both CogA and PhysA used in the present chapter were based on self-report. Self-report measures have been previously found to lead to an underestimation of the strength of the relationship between the self-reported PhysA and the actual behaviour (Celis-Morales et al., 2012). Furthermore, other unobserved variables could have influenced the relationships between CogA/PhysA and the test scores.

11.6 Conclusion

The possible confounding effects of CogA and PhysA on the language group differences observed in three data sets of this study were examined in the present chapter. The present analysis offers limited evidence of the influence of PhysA, and none at all of CogA on the three language groups' performance. However, the finding that trilinguals' negative effect of PhysA may have modulated their negative IOR global RT performance (and trilinguals' 1-back RT performance on the N-back), indicates that studies investigating trilingualism, and bilingualism and cognition, need to control for PhysA, particularly on RTs measures. Nevertheless, this needs to be confirmed and investigated in more detail before making any concrete conclusions.

11.7 Chapter summary of key points

- Since previous research on the bilingual advantage in EF is not conclusive, more possible confounding elements, which are likely to affect cognitive performance, need to be explored.
- Evidence suggests that engaging in CogA and PhysA enhances cognitive performance, including EF.
- The current study investigated the possible effects of CogA and PhysA engagement on three data sets from the current thesis (focusing on the test score where significant between group differences were found).

- CogA did not predict performance on any of the test scores, which may be due the fact that the participants in the present study did not engage much in CogA.
- The current analysis suggests that PhysA cannot explain the trilingual disadvantage found for the Simon effect (Chapter 5), the Stroop effect or the Stroop incongruent condition (Chapter 8).
- The current analysis provides some, but limited, evidence of the modulation effect of PhysA in the N-back task, although it may explain the trilingual disadvantage in IOR global RT.
- PhysA may modulate RT performance on EF tests and therefore this needs to be accounted for when comparing language groups.
- Further research is needed to fully understand the possible modulation effects of PhysA on monolinguals, bilinguals and trilinguals' cognitive performance.

Chapter 12: General conclusion

12.1Thesis summary

The main objective of the work presented here was to address an important gap in the literature – whether the proposed bilingual advantage in cognitive control (e.g., Bialystok et al., 2012) can be extended to young and older trilingual adults, and whether trilinguals have stronger cognitive control than bilinguals. Addressing this gap is imperative as bilingualism has been suggested to be a significant contributing factor to cognitive reserve, as a result of enhanced cognitive control, and consequently is thought to delay the onset of the clinical expression of MCI and dementia (Bialystok et al., 2014; Alladi et al., 2013; Ossher et al., 2013; Schweizer et al., 2012; Gollan et al., 2011; Chertkow et al., 2010; Craik et al., 2010; Bialystok et al., 2007). Given the brain's plasticity and evidence of this in bilinguals (e.g., Abutalebi et al., 2015; Olsen et al., 2015; Schweizer et al., 2012; Luk et al., 2011a), and a recent finding of a trilingual advantage in cognitive control in children (Poarch and van Hell, 2012), a trilingual advantage in adults is a likely possibility.

The thesis also investigated any age effects, an aspect important to address in trilinguals, as this had not been previously investigated in the literature. Age was examined on a continuum (from young to older adults) rather than in predetermined age groups, which seems to be the trend in the bilingual advantage literature (e.g., Salvatierra and Rosselli, 2010; Bialystok et al., 2004). As the bilingual advantage in cognitive control is least likely to be seen in young adults (Hilchey and Klein, 2011), it is necessary to discover at what exact age bilinguals, and more importantly, trilinguals start modulating cognitive control. This is difficult to achieve by assigning participants to predetermined age groups. Also, given that the trajectory of the ageing process on cognitive function is heterogeneous and complex (e.g., Hartshorne and Germine, 2015; Salthouse, 2009a) it is better to examine age on a continuum, as this can provide a clearer picture of any age-related effects.

Task complexity was also important to address in trilinguals, as it had been previously proposed that in young adults any advantages would most likely be seen in more demanding conditions (Bialystok et al., 2012). As the literature has provided mixed findings regarding whether AoA and language use predict bilinguals' performance on cognitive control tasks, it was essential to focus on these factors too, especially in trilinguals. Lastly, given recent non-bilingual advantage results (although not that many had been reported prior to the start of this project), any possible confounding factors needed to be considered; these were addressed in the thesis by looking at physical activity and cognitive activity, which had not been previously directly investigated in trilinguals, or bilinguals. Both of these factors have been found to modulate EF (see Chapters 2 and 3).

The thesis aimed to carefully control the language groups; monolinguals were not functionally fluent in any other language except their L1; bilinguals only spoke two languages, and on a daily basis; and trilinguals only spoke three languages, and on a daily basis. This is imperative, especially considering that it has now emerged that not all studies adequately control for trilinguals or multilinguals in their "bilingual" group (e.g., Coderre and van Heuven, 2014; Alladi et al., 2014; Paap and Sawi, 2014; Paap and Greenberg, 2013). Thus, carefully separating the language groups should give an indication as to whether trilinguals, or multilinguals who have been included in a "bilingual" cohort in previous studies in the literature, may have influenced earlier findings.

The bilinguals and trilinguals recruited for this thesis had various languages as their first, second and third, and came from different cultural backgrounds, but all lived in the multicultural city of Bradford. Thus, the trilinguals, and bilinguals in this thesis are representative of many bilinguals and trilinguals in the world, and therefore it was important to address the hypothesised trilingual advantage in this population. Finding trilinguals can be difficult and therefore Bradford is an excellent location for experiments such as those presented here.

Both trilinguals and bilinguals had balanced proficiency in L1 and L2, and trilinguals in L1, L2, and L3 (Chapter 9). Some had used more than one language all their lives, whilst others only for a short period of time. An advantage in cognitive control has been reported in adult L2 language learners, compared to monolinguals (Linck et al., 2008), so having a wide range of AoA was not predicted to be disadvantageous for the bilinguals and trilinguals recruited for this thesis. Unsurprisingly, residing in a country where English is the official language, bilinguals used L2 (English) more than L1 on a daily basis and trilinguals L3 (mostly English), most of them on a daily basis, although this did not always reach significance. How balanced their daily use was, was measured on a continuum from dominant to balanced use. Both early and late L2 AoA trilinguals and bilinguals were recruited to investigate the possible relationship between AoA and test performance on a continuum. As was stated in Chapter 1, it was essential to examine both factors on a continuum, as bilingual experience should not be treated as a categorical variable. Years of education were taken as a measure of SES (Bialystok et al., 2008; Emmorey et al., 2008) in all experiments, although, in addition to this, more sensitive controls were introduced as the thesis progressed (see below).

Chapter 5 investigated the proposed bilingual advantage in inhibitory control and monitoring (measured by the Simon task), as well as age-related effects in 18 to 70 year olds. The data suggest that age predicted inhibitory control in trilinguals only, showing the novel and surprising finding of a trilingual **disadvantage** (compared to monolinguals and bilinguals) after around 29 years of age. This indicates that if age is to be investigated by predetermined groups in adults, groups should be divided into before and the age of 29 years. In terms of monitoring, trilingualism and monolingualism were affected by age, but not bilingualism. However, no age-related differences in monitoring were modulated by language group. These results suggest that monolingualism and bilingualism, but not trilingualism, attenuate age-related decline in inhibitory control. In terms of bilingualism, this is not in line with Bialystok et al. (2004), Salvatierra and Rosselli (2010) or Schroeder and Marian (2012), who found only bilingualism to attenuate age-related decline in inhibitory control, but not monolingualism. Importantly, the data suggest that including trilinguals in a bilingual sample could have skewed data from previous studies, and future studies need to control for a possible confounding effect of having trilinguals or multilinguals in their "bilingual" cohort.

As inhibitory control and WM have been argued to share a common underlying mechanism (e.g., Miyake and Friedman, 2012), **Chapter 6** examined WM, and possible age-related effects (in 18 to 79 year olds), on a complex numerical version of the N-back task (1-back and 2-back). This particular version of the N-back task had not been used before to investigate WM in bilinguals or trilinguals. In line with Chapter 5, a trilingual **disadvantage** was observed in both 1-back and 2-back (both match and non-match trials), as well as in the n-back effect (match). Furthermore, a bilingual **disadvantage** was also seen in 1-back and 2-back (non-match) and marginally in 2-back (match). However, unlike the results seen in the Simon task in Chapter 5, no clear differences were found between bilinguals and trilinguals. The data suggest that in terms of RTs the more languages participants spoke the worse they performed, but this did not reach significance between bilinguals and trilinguals. This suggests that managing two or three languages, compared to just one, can have a negative impact on WM, as was seen with inhibitory control (Chapter 5). Age significantly predicted WM performance, whereby reaction time increased with age, although this age-related decline was not modulated by language group, unlike what was seen with inhibitory control (Chapter 5). The results support the view that inhibitory control and WM share the same underlying mechanism (Miyake and Friedman, 2012). However, the fact that the same age-related differences between the language groups were not observed in Chapters 5 and 6 suggests it is more complicated than Miyake and Friedman's conclusion. The crossover at 29 years of age (Chapter 5), after which trilinguals were observed to have a disadvantage compared to the other two language groups, suggests that inhibition and WM sharing the same underlying mechanism may actually be age-dependent, and only be the case in young adults aged 29 years and younger. Furthermore, as mentioned in Chapter 2 (section 2.2) the trajectory of the ageing process on cognitive function is both heterogeneous and complex. The finding that trilinguals' inhibitory control starts to decline after the age of 29 years compared to the other language groups, whilst WM capacity is unaffected by age, suggests that some of the proposed variability in age-related cognitive performance may be explained by how many languages an individual speaks.

Having observed a trilingual **disadvantage** in inhibitory control and WM, and a bilingual **disadvantage** in WM, begged the question whether inhibitory control measured by other interference tasks would show similar effects. The next two chapters investigated this along with possible age-related effects (18 to 79 year olds) on two different tasks; the IOR task and the Stroop task. This time, another measure was added to control for SES, including education, namely occupational status. Although subjective and objective measures of language proficiency have been found to strongly correlate (Luk and Bialystok, 2013; Marian et al., 2007), an objective language proficiency measure was also employed to investigate whether trilinguals and bilinguals would show the same results of proficiency, both according to objective and subjective measures, which they did.

In **Chapter 7,** performance in the IOR task was examined. Previous limited studies have examined the bilingual advantage on this task in young adults, producing conflicting results, and none have looked at this in trilinguals. Furthermore, in the IOR task, age effects have not previously been investigated in trilinguals, or bilinguals. The experiment of Chapter 7, demonstrated a trilingual **disadvantage** in global RT (monitoring) compared to monolinguals, but not on the inhibitory control measure, the IOR effect. The finding that all groups were statistically similar in terms of the IOR effect is in line with the findings of Hernández et al. (2010) and Costa et al. (2008) who did not find a modulation effect of language group when comparing young adult monolinguals and bilinguals. Although the **disadvantage** matched that of previous chapters (5 and 6), it was only seen in terms of monitoring. An age-related decline was observed in this task, both in terms of accuracy of response and global RT, as well as for the IOR effect, although this was not modulated by language group.

In **Chapter 8,** performance on the Stroop colour-word task was investigated. Previous studies have reported a bilingual advantage on this task, as well as numerical and spatial versions, which was not supported by the findings of this experiment as monolinguals and bilinguals performed statistically similarly. Performance by trilinguals on this task had not been investigated prior to the start of this project. A trilingual **disadvantage** was observed in inhibitory control, consistent with results from Chapter 5 (Simon task), but not Chapter 7 (IOR task). Although linguistic interference is expected in the Stroop task, this suggests that the Simon task and the Stroop task tap similar aspects of inhibitory control, but not the IOR task. There was no statistical difference between bilinguals and trilinguals, suggesting that three languages are neither better nor worse than two languages in terms of Stroop task performance. An age-related decline was observed on both congruent and incongruent conditions of the task, although, as was observed in Chapters 6 and 7, this was not modulated by language group.

Chapter 9, the last experimental chapter, investigated task complexity in 19 to 55 year olds, which was important to address given the bilingual and trilingual **disadvantages** in previous chapters, and because it has been be proposed that in young adults, bilingual advantages are most likely to be seen in more demanding conditions (Bialystok et al., 2012). The Simon task (two levels of complexity) and N-back task (four levels of complexity) were chosen as they are excellent candidates for manipulation of task levels. As previous chapters had shown bilingual and trilingual **disadvantages**, some potential methodological concerns were also addressed. Further measures were introduced to control for (or match) the language groups on SES. Although non-verbal reasoning is not thought to be related to inhibition (Friedman et al., 2006), WM updating is (Friedman et al., 2006), and given that in these paradigms the updating demands are high, participants' non-verbal reasoning was also measured. Another methodological concern in the previous chapters was that the scale (1 to 5) of the language proficiency measure was not sensitive enough; the scale was therefore changed here to range from 1 to 10.

In the Simon task, a bilingual **disadvantage** was observed (compared to monolinguals), in the complex condition, but only in terms of accuracy of response. No other language group differences were seen. Several trends towards significance language group differences were observed in the N-back task, although these did not yield statistical significance. That is, the groups did not statistically differ under any level of complexity, nor when subjected to an increasing WM load between 0-back and the more complex conditions (1-back, 2-back and 3-back). Non-verbal reasoning was significantly higher for monolinguals than trilinguals, but no difference between monolinguals and bilinguals was detected. Furthermore, this did not change the results when the non-verbal reasoning measure was taken out of the model. Thus, the fact that monolinguals scored higher than trilinguals in non-verbal reasoning, but did not score statistically different from bilinguals, is not likely to explain the observed bilingual **disadvantage**.

This lack of replication from Chapters 5 and 6 is perplexing, although as this thesis has previously shown, it is not uncommon in the bilingual cognitive control literature. One possible explanation could be the age range. The individuals who took part in this experiment were younger to middle aged adults, but in Chapters 5 and 6, the age ranged from young to older adults. Another possible explanation for the neutral results, apart from the bilingual **disadvantage** on one of the Simon task measures, is that fewer participants were recruited for the experiment in Chapter 9 than in Chapters 5 and 6, which may have influenced the results. However, it has been recently argued that a difference between bilinguals and monolinguals (bilingual advantage) is more likely to be seen in studies with small sample sizes, as opposed to large sample sizes (Paap et al., in press). Furthermore, the lack of consistent language group differences may also be due to the fact that levels of complexity in both tasks were completed consecutively. For example, on the N-back task, participants completed level 0, followed by 1 and so forth. This may have introduced a practice effect. However, participants also completed the two levels in the N-back task in Chapter 6 consecutively, which resulted in aforementioned language group differences. Lastly, the language proficiency scoring was different than in Chapters 5 and 6, whereby the scale was changed from zero to five into zero to ten, although this is not likely to have influenced the result. Nevertheless, the bilingual **disadvantage** found on the Simon task is of interest. The results of Chapter 9 are thus partly in line with Hlichey and Klein's (2011) conclusion that a difference between monolinguals and bilinguals (i.e., a bilingual advantage) is least likely to occur in young adults, although in this case the difference was expected to go either way, which did not happen. Importantly, these results do not fully support Bialystok et al.'s (2012) hypothesis that differences between language groups are more likely to be seen in more demanding conditions, as a difference was only observed in one of many measures on these tasks.

Chapter 10 examined whether L2 AoA and language use predicted bilinguals and trilinguals' test scores. Three data sets (from Chapters 5, 6, 7, and 8) from the current thesis were examined for this purpose. There is some evidence suggesting that these factors modulate bilinguals' performance, although the evidence is not conclusive. Prior to the start of this project this had not been previously investigated in trilinguals and therefore it was important to include it in the current thesis. The data suggest that L2 AoA did not predict test scores in bilinguals, nor did L2 AoA predict trilinguals' test scores, providing new evidence that L2 AoA does not modulate cognitive control in trilinguals. Language use did not conclusively predict test scores among bilinguals. Its effects were, however, seen in the N-back task, but not consistently, indicating worse performance for more dominant bilinguals. This finding was only consistent with one of the bilingual **disadvantage** findings (2-back non-match) in

Chapter 7. Language use did not predict any of the test scores among trilinguals.

Lastly, **Chapter 11** investigated two potential confounding factors – cognitive activity and physical activity – both of which, according to previous research, are likely to influence cognitive performance (see Chapters 2 and 3). Examining these is particularly important given the inconclusive findings in the literature, and the interesting bilingual and trilingual **disadvantages** findings of this thesis. Both cognitive activity and physical activity have been associated with enhanced EF (see Chapters 2 and 3). The same three data sets as were utilised in Chapter 10 were examined, with a focus on the test scores which produced significant results. Cognitive activity did not modulate performance, which can possibly be explained by the fact that the participants did not report much engagement in cognitive activities, or that the measure of cognitive activity was not sensitive enough. The data indicates that there may have been some modulation effect of physical activity. It may explain the trilingual **disadvantage** in IOR global RT (Chapter 7) whereby worse monitoring was associated with increased level of physical activity for trilinguals, but vice versa for the other language groups. Physical activity may also have modulated the trilingual **disadvantage** in the N-back task (1-back), whereby older trilinguals demonstrated increasing RTs with increased physical activity. However, the data suggest this did not explain the trilingual **disadvantage** observed in inhibitory control in Chapter 5 (Simon effect) or 8 (Stroop effect and incongruent condition). The finding that increased physical activity was associated with worse performance is a surprising one since this goes against the general result in the literature that increased physical activity is associated with increased alertness, which in turn has a positive effect on EF.

To summarise, contrary to the initial hypothesis, this thesis observed a trilingual and bilingual **disadvantage** in cognitive control. Although an age-related decline was observed on most measures, age was only modulated by language group in the Simon task, where the novel finding of a trilingual

disadvantage was observed in participants older than 29 years of age. Language AoA and language use did not conclusively modulate bilinguals and trilinguals' performance, and the significant findings cannot be accounted for by cognitive activity; some, however, may be explained in terms of physical activity, although the evidence for this was not consistent and more research is needed. Significantly different performance was seen between bilinguals and trilinguals in the Simon task (Chapter 5), where bilinguals showed stronger inhibitory control after 29 years of age. However, this was not consistently replicated in the following experiments, suggesting that if there is a difference between these groups it is a very subtle one, and only occurs under certain circumstances, or that more participants were needed in the trilingual groups. The data suggest that on the N-back, for instance, RT performance decreased with increasing number of languages, but this did not yield significance.

12.2 Other possible explanations, limitations and future studies

As with all experiments, there may be other possible explanations for findings. It seems unlikely that the finding of a trilingual **disadvantage** means these were just bad trilingual groups, as there is no reason to suppose that they should be any worse than the other two groups. In addition, the fact that a bilingual **disadvantage** was also observed makes it even less likely. Actually, the results of this thesis indicate that the proposed bilingual advantage is not as prominent as the (initial) literature suggested. It has been argued by Paap et al. (in press) that *"either bilingualism does not enhance EF in any circumstance or only very specific, but undetermined, circumstances"* (p.2). They base this conclusion both on their data and other studies, but their data has one issue – the definition of a bilingual. Interestingly, and as previously mentioned, Paap and Greenberg (2013) observed no difference in monitoring between young monolinguals and bilinguals, but did observe a bilingual **disadvantage** in inhibitory control. In a later study, Paap and Sawi (2014) observed a bilingual **disadvantage** in both inhibitory control and monitoring. Their lab then pooled these data (Paap et al., 2014), and investigated the effect of number of languages. This time they observed a bilingual, and a trilingual **disadvantage**, in inhibitory control (compared to monolinguals), which is in line with the findings of the present thesis. Although they did not detect a significant difference between bilinguals and trilinguals, this indicates (as do the findings of this thesis) that trilingualism may influence bilinguals' outcomes on such tests. Thus, it is imperative for future studies to separate bilinguals and trilinguals (and other multilinguals). Lastly, it needs to be determined why trilinguals and bilinguals do sometimes show worse performance than monolinguals, and why trilinguals sometimes show worse performance compared to bilinguals (and monolinguals). As mentioned in Chapter 4, this could be due to trilinguals having more languages to inhibit/ignore than bilinguals and monolinguals (and bilinguals versus monolinguals), consequently having less processing power to deal with conflicting information, i.e., attention overload. However, as trilinguals were only outperformed by bilinguals on one measure in this thesis (Simon effect), it is possible that although structural and functional differences between trilinguals and bilinguals may exist (see Chapter 3), it does not necessarily mean that these two language groups are more likely to perform similarly than differently. Thus, despite the fact that trilinguals have to inhibit/ignore more languages than bilinguals, and their brains differ in terms of structure and function, they may actually use their brains *as* effectively in most cases.

As previous research into age-related effects of bilingualism on cognitive control (e.g., Bialystok et al., 2004) indicates that the differences between monolinguals and bilinguals increase with age, to the advantage of bilinguals, it was an expected finding in the present thesis. However, this thesis showed that age was only modulated by language group in terms of inhibition (only the Simon task), where trilinguals older than around 29 years of age demonstrated worse inhibition that their monolingual and bilingual counterparts. Thus, Bialystok et al.'s (2004) finding was not replicated in terms of bilingualism, and the novel and unexpected finding of a trilingual **disadvantage** suggests an opposite pattern with age for trilinguals. The reason for the general finding (except the trilingual **disadvantage** seen in Chapter 5) of no modulation effect of language group on age may be that in the chapters which specifically looked at age, variability in terms of age may not have been widespread enough to detect a difference between the language groups or to look at on a continuum, especially in Chapters 7 and 8, where sample size was smaller than in Chapters 5 and 6. It is, however, unlikely that this can explain the finding in Chapter 6, in which sample size was similar to that of Chapter 5.

This thesis indicates that the factors closely related to bilingual and trilingual experience – AoA and language use – are not important in terms of test performance. That is, whether languages are acquired early or late, or are used in a balanced way or not, does not determine whether differences between language groups are seen. Some could argue that the results might have been different if the groups had been divided into early versus late acquisition, and balanced versus dominant language use. Although not reported in Chapter 10, this method was also applied in order to see whether a different pattern would emerge, but no change was noted in the results. The AoA results support the finding of Linck et al. (2008) in that stronger inhibitory control is not always associated with early AoA in bilinguals compared to monolinguals. The finding that language use is not an important predictor of performance matches that of Soveri et al. (2011), who recruited Finnish/Swedish bilinguals, and partly that of Goral et al. (2013), who recruited Spanish/English bilinguals. Current trilinguals and bilinguals had various languages, which Soveri et al. (2011) and Goral et al. (2013) did not look at. This further indicates that whether bilinguals and possibly trilinguals speak various languages or the same is not important in terms of test performance. It has been argued (Luk et al., 2011b) that onset age of active bilingualism is a more sensitive measure than onset age of acquisition of L2. It is possible that looking at active trilingualism/bilingualism would have changed the results. Future studies should take this into consideration.

The thesis also indicates that physical activity, which is known to influence cognitive control, may have influenced previous findings in the literature and therefore needs to be controlled in future studies. Cognitive activity, on the other hand, did not prove to be a significant influencing factor; however, this measure may not have been sensitive enough to detect any influences. Future studies should investigate this factor further, and examine each cognitive activity factor independently, rather than as a composite score.

It has been argued (for example, Paap et al., in press; Hilchey and Klein, 2011) that some of the bilingual advantages reported in the literature may be due to immigrant status, and the reasoning behind this speculation is that immigrant status is positively associated with higher intelligence, and thus for some studies the bilingual advantage may simply have been due to higher intelligence in the bilinguals, who happened to be more intelligent. However, the data presented here suggest otherwise. A proportion of the trilinguals and the bilinguals were immigrants who were outperformed by monolinguals on some of the measures in this thesis, and performed similarly on others. Also concerning the Simon task, trilinguals were outperformed by bilinguals in terms of inhibitory control; here, more of the trilinguals were second generation individuals who had lived in the UK from birth, whilst most of the bilinguals were immigrants. Future studies investigating trilinguals and bilinguals could divide each language group into immigrant versus home group, to investigate this further.

It could be argued that since the bilinguals and trilinguals had various languages this could have influenced the results. This has indeed been conjectured (e.g., Hilchey and Klein, 2011). Support for this argument may come from studies by Paap and Greenberg (2013) and Paap and Sawi (2014), who recruited young bilinguals with various L1 languages, and either found no difference or a bilingual **disadvantage** in the Simon task, which may, in turn, be explained by various L1 languages. However, at least two studies which employed bilinguals from various cultural and language backgrounds found a bilingual advantage (Bialystok et al., 2014; Luo et al., 2013). Furthermore, Kirk et al. (2014), who directly investigated whether cognitive control advantages are related to differences in cultural and ethnic background, found no evidence of such a relationship. Hence, various languages of bilinguals and trilinguals should not make a bilingual and a trilingual advantage less likely to be seen. Thus, given these inconsistent accounts it is likely that other, unknown, factors may have influenced Paap and colleagues' findings. They could for instance be explained by the fact that their "bilingual" cohorts were confounded by multilinguals. The latter speculation seems more reasonable, as variability in L1 and cultural background could be seen as a positive control for any potential confounding effects of language and cultural backgrounds. The trilingual/bilingual **disadvantage** and neutral findings presented here may be an addition to a covert side of this literature. A side that suggests that the bilingual advantage is less prominent than it appears to be.

A recent meta-analysis by De Bruin et al. (2014) investigated whether the bilingual cognitive control advantage literature may be influenced by publication bias and file-drawer bias. They examined conference papers on the bilingual advantage and cognitive control, from 1999 to 2012, and identified which of these were then subsequently published. They observed that the abstracts that challenged the bilingual advantage were the least likely to get published. Out of 104 abstracts, 52 papers were published. Of the papers supporting the bilingual advantage, 68% were published, but if they challenged it; that is, either found no difference, or a bilingual **disadvantage**, 29% were published. De Bruin et al. (2014) further observed that the supportive and challenging studies had similar power to detect a difference, and that the difference in publication was not due to sample size of the studies. The authors suggested the reason for this may be a combination of the "file-drawer bias" (see Spellman, 2012 for a discussion of this in the psychology literature) and publication bias. That is, researchers are more likely to ignore experiments that "didn't work" or go against the literature, and editors are less likely to accept papers that do not support the literature, or show null results. The authors admitted to having published a paper, which only included the one experiment out of three that showed a bilingual advantage, and later to have ignored an attempted replication of this experiment, as it failed to replicate. They further suggested that this bias of reporting mostly positive findings is *"only the tip of the iceberg"* (p.7). Taking this into account, it is imperative that all findings in this literature do get published, as knowledge in this field will not advance unless all aspects have been considered. Therefore, the results of this thesis are as important as positive findings, and will add significant knowledge to the literature.

The first part of this section has recommended some future work related to methodology and highlighted important questions that have arisen from this project. Further work should replicate the work presented here. This should be investigated in all age groups, from early childhood to older adults, utilising both a cross-sectional design and a longitudinal design. Further studies should also investigate trilingualism on one aspect of cognitive control that has been implicated in the bilingual advantage, but was not investigated in the current thesis, namely task-switching (attention/set shifting) (for a review, see Bialystok et al., 2012). Also, future work should extend the investigation of trilingualism and cognitive control to quadrilinguals, quintilinguals and so forth. Furthermore, other functions that have been associated with bilingual advantage, such as episodic memory and creativity are also important to address in trilinguals.

12.3 Implications

The results presented here are important for the bilingualism and cognitive control literature and, now significantly, the under-researched trilingualism literature. They highlight an issue in the literature of not separating bilinguals from individuals who speak more than two languages, which could be one of the reasons for inconsistent results in the literature. Thus, researchers in this area need to separate bilinguals from trilinguals, trilinguals from quadrilinguals and so on. Another implication is that trilinguals' performance on tests of cognitive control may be modulated by their level of physical activity. This needs to be taken into consideration in future work.

As for the main objective of this thesis, to assess whether trilinguals demonstrate stronger cognitive control than bilinguals (and monolinguals), the novel findings presented here, suggest that this is indeed not the case in young to older adults. On the contrary, the results suggest that trilinguals can, under some circumstances, display worse cognitive control compared to both monolinguals and bilinguals, although more evidence of this was found in monolinguals here. Additionally, evidence suggests both structural and functional differences (see Chapter 3) between bilinguals and trilinguals, but the findings of this thesis suggest this may not be detected by tests such as those used in this thesis, with the exception of the Simon task. This indicates that perhaps the Simon task is more sensitive, and thus better suited to investigate differences between trilinguals and bilinguals than the Stroop task, IOR task and the N-back task.

Furthermore, as it has been proposed that speaking more than one language is a contributing factor to cognitive reserve, and may delay the onset of clinical expression of dementias such as AD, the results presented here have implications for the cognitive reserve literature and consequently for dementia. The general consensus is that the higher the reserve, the greater is the brain decline required before individuals start to show deterioration on clinical diagnostic tests, such as the MMSE (Satz et al., 2011; Sachdev and Valenzuela, 2009; Satz, 1993). Investigating trilingualism (and bilingualism) as potential cognitive reserve variables is, therefore, important, as better understanding is needed to develop more sensitive measures in order to detect cognitive decline sooner in those with high cognitive reserve. As mentioned in Chapter 2, increasing evidence suggests that compared to monolingualism, bilingualism delays the onset of clinical expression of AD (Bialystok et al., 2014; Gollan et al., 2011; Craik et al., 2010; Bialystok et al., 2007), but two new recent studies did not report such an effect (Zahodne et al., 2014; Yeung et al., 2014), and Chertkow et al. (2010) observed that speaking three or more languages is needed to see this protective effect. Thus, current evidence is conflicting and large scale studies will help determine the proposed protective impact of bilingualism, trilingualism and multilingualism.

This thesis investigated whether trilinguals encompass higher cognitive control than bilinguals – and in line with the finding by Chertkow et al. (2010) – it speculated that if this is the case, it could indicate that trilingualism would further delay the onset of clinical expression of dementia. It is still unclear why, compared to monolinguals, bilinguals are able to tolerate more neuropathological damage before showing signs of cognitive decline, and no evidence exists comparing trilinguals and bilinguals. However, limited neuroimaging evidence suggests that bilingualism does not directly protect the memory functions initially affected in AD, but rather shields executive control circuits (for a review, see Gold, 2015). Assuming a direct link between cognitive control and AD, the findings of this thesis suggest that under some circumstances monolinguals (and bilinguals) have a higher reserve than trilinguals, and thus may show delayed, rather than early, onset of AD symptoms. Nonetheless, as the research on whether there is a direct link between cognitive control, cognitive reserve and delayed onset of dementia is in its infancy, the present results cannot determine whether the trilinguals in this thesis have less reserve (and thus less protective effect) than bilinguals and monolinguals. Further work will relate these results to the wider field of cognitive reserve, and investigate whether the effect is temporary, or whether monolinguals have a higher reserve than trilinguals (which would go against the literature). Having said this, clinical diagnostic tests that include cognitive control measures should be used with caution as a potential negative influence of trilingualism (and bilingualism) may affect the scores. Thus, it is important that clinicians do not assume a positive influence of speaking two or more languages on cognitive performance. These findings also have implications for wider cognitive research, as all tests that rely on cognitive control may be influenced by how many languages one speaks.

12.4 Thesis conclusion

The present thesis aimed to fill an important gap in the bilingual "advantage" and cognitive control literature, by extending the investigation to the effects of trilingualism in young to older adults. The novel trilingual (and bilingual) **disadvantage** results presented here raise questions about the prominence of the bilingual "advantage", how bilinguals are defined and allocated to groups, and suggests that trilingualism (and bilingualism) can in some cases be detrimental to cognitive control. The work presented here – which is the first to address the question of how trilingualism affects cognitive control in young to older adults, employing various EF tasks that tap inhibition and WM – should provide ample encouragement to future researchers in the field to investigate the effects of trilingualism (and multilingualism) on cognition and the brain.

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Appendix 1

Lifestyle Questionnaire

The purpose of this questionnaire is to explore your physical and mental activeness, as well as your language use. It takes approximately 5 minutes to complete.

Instructions:

Please answer the questions below

Thank you very much for your participation.

Part 1 - General

1. Age:..............

2. Gender (circle one): Female Male

3. Country of origin:...

4. Education (how many years spent in formal education):..

5. What is your present occupational position (or your last position)?…..

Part 2 – language history

6. What is your first (native) language?..

(if you grew up with more than one language, please specify)

7. Please rate your ability in your first/native language

(circle one)

Very poor

Poor

Fair

Good

Very good

8. Do you speak a second language?

Yes

No

<u>If you answered no, skip to Part 3, if you answered yes, please answer the following questions</u>

9. What is your second language?...

10. How many years you have spoken your second language?...

11. Please rate your ability in your second language

(circle one)

Very poor

Poor

Fair

Good

Very good

12. Which language do you usually speak (first or second?)

At home?...

With friends?...

At work (or university)...................................

13. How many hours per day do you watch films, TV or listen to radio in your first and second languages?

(please estimate)

First language.......................hours

Second language..................hours

14. How many hours per day do you read materials such as newspapers, books, magazines in your first and second language?

(please estimate)

First language.....................hours per day

Second language................hours per day

15. a Do you speak more languages fluently? (would be able to easily maintain a conversation)

Yes

No

15. b How many other languages do you speak? ……………………

16. How often do you use your first, second, and third languages on a daily basis?

(please estimate the percentage for each)

First.......................% per day

Second.......................% per day

Third................% per day

Part 3 – Activeness

1. On the scale of 1-10 (1=not active, 10=very active) please rate how active you are on a daily basis

(please circle one)

1 2 3 4 5 6 7 8 9 10

2. Do you do any aerobic exercise (e.g. running, jogging, swimming, bicycling)?

Yes

(if yes, which one/s?)...

No

3. If you answered ‘Yes’, how many hours per week do you spend on this activity?

(Please tick one)

1-2 hours

3-4 hours

5-6 hours

7+ hours

4. In your leisure time, do you walk on a regular basis?

Yes

No

5. If you answered 'Yes', how many hours per week do you spend on this activity?

(Please tick one)

1-2 hours

3-4 hours

5-6 hours

7+

6. How far to you usually walk?

(please tick one)

1-2 miles

3-4 miles

5-6 miles

More than 6 miles

Part 4 – Using your brain

1. Do you do any of the following mental activities on a regular basis? (Please tick all that apply, and tick how often you do the activities)

(a) Sudoku

How often do you do this activity? (tick one)

Every day

4-5 times a week

2-3 times a week

Once a week

Once a month

2-3 times a month

Less often

(b) Crossword puzzles

How often do you do this activity? (tick one)

Every day

4-5 times a week

2-3 times a week

Once a week

Once a month

2-3 times a month

Less often

(c) Play cards – please name the game/s

How often do you do this activity? (tick one)

Everyday

4-5 times a week

2-3 times a week

Once a week

Once a month

2-3 times a month

Less often

(d) Scrabble

How often do you do this activity? (tick one)

Every day

4-5 times a week

2-3 times a week

Once a week

Once a month

2-3 times a month

Less often

(e) Brain training exercises/games such as “brain age” by Nintendo – please name

…...

…...

How often do you do this activity? (tick one)

Every day

4-5 times a week

2-3 times a week

Once a week

Once a month

2-3 times a month

Less often

(f) Play computer/ video games

(please name the game/s)

……………………………………………………………………………………………

……………………………………………………………………………………………

How often do you do this activity? (tick one)

Every day

4-5 times a week

2-3 times a week

Once a week

Once a month

2-3 times a month

Less often

(g) Other mental activities (e.g chess)

How often do you do this activity? (tick one)

Every day

4-5 times a week

2-3 times a week

Once a week

Once a month

2-3 times a month

Less often

(h) No – none above

Part 4 – Diet

29. Do you consume turmeric on a regular basis (turmeric is an Indian spice used in curry powder)?

(circle one)

Yes

No

30. If you answered 'Yes', during the past 12 months did you consume it

(tick one)

A few days per month

1-3 days per week

4-6 days per week

Every day

THANK YOU.

Appendix 2

Lifestyle Questionnaire

The purpose of this questionnaire is to explore your physical and mental activeness, as well as your language use. It takes approximately 5 minutes to complete.

Instructions:

Please answer the questions below

Thank you very much for your participation.

Part 1 – General

1.1

Participant code:		**Today's date:**		
Age:		**Gender: (please circle)**	Male Female	

1.2

Country of origin:	

1.3

How long have you lived in the UK?	

1.4

How many years have you spent in formal education?	

1.5

Circle the number that best describes the highest educational level obtained by <u>you</u>:	(1) Less than high school (2) Graduated from high school (3) Professional training (4) Some college or university (5) Earned a bachelor's degree from college or university (6) Earned a postgraduate diploma (7) Earned a master's degree (8) Earned a Ph.D. (9) Earned a M.D. (10) Other

1.6

Circle the number that best describes the highest educational level obtained by <u>your mother:</u>	(1) Less than high school (2) Graduated from high school (3) Professional training (4) Some college or university (5) Earned a bachelor's degree from college or university (6) Earned a postgraduate diploma (7) Earned a master's degree (8) Earned a Ph.D. (9) Earned a M.D. (10) Other

1.7

Circle the number that best describes the highest educational level obtained by <u>your father:</u>	(1) Less than high school (2) Graduated from high school (3) Professional training (4) Some college or university (5) Earned a bachelor's degree from college or university (6) Earned a postgraduate diploma (7) Earned a master's degree (8) Earned a Ph.D. (9) Earned a M.D. (10) Other

1.8

Circle the number that best describes your <u>mother's</u> occupational status:	(1) Professional and managerial (examples: business man, lecturer, engineer, IT management, teacher) (2) Administrative and secretarial (examples: school secretary, receptionist) (3) Skilled manual work (examples: chef, mechanic, joiner, butcher, electrician)

	(4) Semi and unskilled manual work (example: sales assistant, labourer, delivery driver, waitress and childcare worker) (5) Unemployed (6) Other

1.9

Circle the number that best describes your <u>father's</u> occupational status:	(1) Professional and managerial (examples: business man, lecturer, engineer, IT management, teacher) (2) Administrative and secretarial (examples: school secretary, receptionist) (3) Skilled manual work (examples: chef, mechanic, joiner, butcher, electrician) (4) Semi and unskilled manual work (example: sales assistant, labourer, delivery driver, waitress and childcare worker) (5) Unemployed (6) Other

1.10

Please indicate to which socio-economic group you believe you belong to (please circle one):	(1) Lower middle class (2) Middle class (3) High middle class (4) Working class (5) None of the above

<u>If you only speak one language please go to part 3.</u>

<u>Part 2 – language experience and proficiency</u>

2.1

Please list all the languages you know **in order of dominance:**

1	2	3	4

2.2

Please list all the languages you know **in order of acquisition** (your native language first):

1	2	3	4

2.3

Please list what percentage of the time you are currently and on average exposed to each language *(your percentages should add up to 100%)*

List language here:				

List percentage here:				

2.4
When choosing to read a text available in all your languages, in what percentage of cases would you choose to read it in each of your languages? Assume that the original was written in another language, which is unknown to you. *(Your percentages should add up to 100%)*

List language here:				
List percentage here:				

2.5
When choosing a language to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each language? Please report percent of total time. (Your percentages should add up to 100%)

List language here:				
List percentage here:				

Please answer the questions below for all the languages you know, each language at a time

2.6.1
Language: ________________________

2.6.2

Began acquiring:	**Became fluent in:**	**Began reading in:**	**Became fluent reading in:**

2.6.3
On a scale from one to ten, please select your level of proficiency in writing, reading, speaking and understanding spoken language. (1 = very poor, 5=average,10 = excellent)

Writing	**Reading**	**Speaking**	**Understanding spoken language**

2.6.4
Please rate to what extent (hours per day on average) you are currently exposed to this language in the following contexts:

Interacting with friends		**Listening to radio/music**	
Interacting with family		**Reading**	

Watching TV		

If you know a second language, please answer the questions below referring to this language

2.7.1
Language: ________________________

2.7.2

Began acquiring:	**Became fluent in:**	**Began reading in:**	**Became fluent reading in:**

2.7.3
On a scale from one to ten, please select your level of proficiency in writing, reading, speaking and understanding spoken language. (1 = very poor, 5=average, 10 = excellent)

Writing	**Reading**	**Speaking**	**Understanding spoken language**

2.7.4
Please rate to what extent (hours per day on average) you are currently exposed to this language in the following contexts:

Interacting with friends		**Listening to radio/music**	
Interacting with family		**Reading**	
Watching TV			

If you know a third language, please answer the questions below referring to this language

2.8.1
Language: ________________________

2.8.2

Began acquiring:	**Became fluent in:**	**Began reading in:**	**Became fluent reading in:**

2.8.3
On a scale from one to ten, please select your level of proficiency in writing, reading, speaking and understanding spoken language. (1 = very poor, 5=average, 10 = excellent)

Writing	Reading	Speaking	Understanding spoken language

2.8.4
Please rate to what extent (hours per day on average) you are currently exposed to this language in the following contexts:

Interacting with friends		**Listening to radio/music**	
Interacting with family		**Reading**	
Watching TV			

2.9
Do you speak more languages fluently? (would be able to easily maintain a conversation) please circle one

Yes **No**

Part 3 – Physical activeness

3.1
On the scale of 1-10 (**1=not active, 10=very active)** please rate how active you are on a daily basis (please circle one)

1 2 3 4 5 6 7 8 9 10

3.2

Do you do any aerobic exercise (e.g. running, jogging, swimming, bicycling)? Please circle one	Yes (if yes, which one/s?) ____ ____ No

3.2.1
If you answered 'Yes', how many hours per week do you spend on this activity? (Please circle one)

1-2 hours	3-4 hours	5-6 hours	7+ hours

3.3

Do you walk on a regular basis? Please circle one	Yes No

3.3.1
If you answered 'Yes', how many hours per week do you spend on this activity? (Please cirlce one)

1-2 hours	3-4 hours	5-6 hours	7+ hours

Part 4 – Musical training experience

4.1
Please rate your overall music ability on the scale of one to 10 (1=poor, 5=average, 10=excellent)

1 2 3 4 5 6 7 8 9 10

4.2
Please list any instrument (s) that you play (including voice) and the years you play each of them, and your ability, beginning with your primary instrument:

Instrument:	**Years playing:**	**Ability on the scale of 1-10 (1=poor, 5=average, 10=excellent)**

4.3
Have you ever had any formal training in music? (if you are a self-taught musician, please also answer **yes**)

- Yes, I had formal training in music
- Yes, I consider myself a self-taught musician
- No

4.4
What type(s) of music training have you had? (check all that apply)

- Private / small group lessons

- Institutional training
- University degree music – list degree:_____________
- Self-taught
- Other (please specify):__________________

4.5
At what age did you begin to study music? __________

4.6
How long did your formal training last? ____________

4.7
How long has it been since you last participated in formal music lessons?

- Currently have one
- Or _______ years

Part 5 – Using your brain

5.1
Do you do any of the following mental activities on a regular basis? Please tick all that apply, and tick how often you do the activities)

5.1.1

Sudoku

How often do you do this activity? (tick one)

1. Every day
2. 4-5 times a week
3. 2-3 times a week
4. Once a week
5. Once a month
6. 2-3 times a month
7. Less often or never

5.1.2
Crossword puzzles

How often do you do this activity? (tick one)

1. Every day
2. 4-5 times a week
3. 2-3 times a week
4. Once a week
5. Once a month
6. 2-3 times a month
7. Less often or never

5.1.3
Play cards – please name the game/s

____

____

How often do you do this activity? (tick one)

1. Everyday
2. 4-5 times a week
3. 2-3 times a week
4. Once a week
5. Once a month
6. 2-3 times a month
7. Less often or never

5.1.4
Scrabble

How often do you do this activity? (tick one)

1.Every day

2.4-5 times a week

3.2-3 times a week

4.Once a week

5.Once a month

6.2-3 times a month

7. Less often or never

5.1.5
<u>Brain training exercises/games such as “brain age” by Nintendo – please name **(there are more answer options below if you do more than one):**</u>

5.1.6.1

____

____

How often do you do this activity? (tick one)

1. Every day
2. 4-5 times a week
3. 2-3 times a week
4. Once a week
5. Once a month
6. 2-3 times a month
7. Less often or never

5.1.6.2

____

____

How often do you do this activity? (tick one)

1. Every day
2. 4-5 times a week
3. 2-3 times a week
4. Once a week
5. Once a month
6. 2-3 times a month

7. Less often or never

5.1.6.3

____

____

How often do you do this activity? (tick one)

1. Every day
2. 4-5 times a week
3. 2-3 times a week
4. Once a week
5. Once a month
6. 2-3 times a month
7. Less often or never

5.1.6.3

____

____

How often do you do this activity? (tick one)

8. Every day
9. 4-5 times a week
10. 2-3 times a week
11. Once a week
12. Once a month
13. 2-3 times a month
14. Less often or never

5.1.7
<u>Play computer games/ video games</u> (please name the game/s)
<u>(there are more answer options below if you do more than one):</u>

5.1.7.1

____

____

How often do you do this activity? (tick one)

1.Every day

2.4-5 times a week

3.2-3 times a week

4.Once a week

5.Once a month

6.2-3 times a month

7.Less often or never

5.1.7.2

How often do you do this activity? (tick one)

1.Every day

2.4-5 times a week

3.2-3 times a week

4.Once a week

5.Once a month

6.2-3 times a month

7.Less often or never

5.1.7.3

How often do you do this activity? (tick one)

1.Every day

2.4-5 times a week

3.2-3 times a week

4.Once a week

5.Once a month

6.2-3 times a month

7.Less often or never

5.1.7.4

How often do you do this activity? (tick one)

1.Every day

2.4-5 times a week

3.2-3 times a week

4.Once a week

5.Once a month

6.2-3 times a month

7.Less often or never

5.1.8
Other mental activities (e.g chess) (please name)
(there are more answer options below if you do more than one):

5.1.8.1

How often do you do this activity? (tick one)

1.Every day

2.4-5 times a week

3.2-3 times a week

4.Once a week

5.Once a month

6.2-3 times a month

7.Less often or never

5.1.8.2

How often do you do this activity? (tick one)

1.Every day

2.4-5 times a week

3.2-3 times a week

4.Once a week

5.Once a month

6.2-3 times a month

7.Less often or never

5.1.8.3

How often do you do this activity? (tick one)

8.Every day

9.4-5 times a week

10. 2-3 times a week

11. Once a week

12. Once a month

13. 2-3 times a month

14. Less often or never

5.1.8.4

How often do you do this activity? (tick one)

15. Every day

16. 4-5 times a week

17. 2-3 times a week

18. Once a week

19. Once a month
20. 2-3 times a month
21. Less often or never

THANK YOU.

Appendix 3

Table 11. Mean accuracy scores (%) and standard errors (SE) for 0 to 3-back conditions in the N-back task, by language group

	Monolinguals		Bilinguals		Trilinguals	
	Mean	SE	Mean	SE	Mean	SE
ACC						
0-b M	94.29	1.19	94.74	0.89	97.63	1.12
0-b NM	98.65	0.56	98.08	0.42	98.78	0.53
1-b M	83.31	3.03	85.35	2.28	88.49	2.85
1-b NM	96.74	1.68	95.24	1.27	96.78	1.58
2-b M	83.18	4.26	76.40	3.22	83.22	4.02
2-b NM	91.73	2.16	91.79	1.63	92.91	2.04
3-b M	72.78	3.95	62.2	2.98	66.07	3.73
3-b NM	88.42	4.10	76.82	3.10	84.10	3.87

Table 12. Mean RTs (ms) and standard errors (SE) for 0 to 3-back conditions in the N-back task, by language group

	Monolinguals		Bilinguals		Trilinguals	
	Mean	SE	Mean	SE	Mean	SE
RT						
0-b M	443.19	14.46	463.13	10.91	451.23	13.64
0-b NM	439.19	16.63	449.84	12.55	458.91	15.69
1-b M	537.66	28.36	524.81	21.41	551.25	26.75
1-b NM	545.41	29.84	573.67	22.52	576.01	28.15
2-b M	650.05	50.24	653.16	37.93	679.44	47.40
2-b NM	659.72	52.63	665.93	39.73	683.69	49.65
3-b M	651.81	54.76	731.38	41.33	823.54	51.66
3-b NM	690.05	69.75	746.14	52.65	813.82	65.80

Table 13. Mean accuracy scores (%) and standard errors (SE) for the N-back effects, by language group

		Monolinguals		**Bilinguals**		**Trilinguals**	
ACC	Effects	Mean	SE	Mean	SE	Mean	SE
Match							
	0-1	10.99	2.92	9.39	2.21	9.14	2.76
	0-2	11.11	4.05	18.35	3.06	14.41	3.82
	0-3	21.51	3.76	32.55	2.84	31.56	3.55
Non-match							
	0-1	1.90	1.78	2.84	1.35	2.00	1.68
	0-2	6.91	2.27	6.30	1.72	5.87	2.15
	0-3	10.23	4.13	21.27	3.12	14.68	3.90

Table 14. Mean RTs (ms) and standard errors (SE) for the N-back effects, by language group

		Monolinguals		Bilinguals		Trilinguals	
RT	Effects	Mean	SE	Mean	SE	Mean	SE
Match							
	1-0	94.46	23.41	61.68	17.67	100.02	22.09
	2-0	206.86	44.92	190.03	33.91	228.21	42.38
	3-0	208.62	51.73	268.26	39.15	372.31	48.80
Non-match							
	1-0	106.23	21.25	123.83	16.04	117.10	20.05
	2-0	220.53	46.95	216.09	35.44	224.77	44.29
	3-0	250.86	67.58	296.31	51.02	354.90	63.76